

## 4. SUMMARY AND CONCLUSIONS

Defensibly estimating the long-term durability of cementitious waste forms, though critically important, is complex, and consensus on how to define and quantify durability does not currently exist. At present, the most extensive set of durability tests simply address long-term durability through simple measures of short-term leach resistance (e.g., ANS/ANSI-16.1).

Leachability indexes were measured for calcium, aluminum, and silicon in each of five grout formulations using the ANS/ANSI-16.1 leaching procedure. The average leach indexes for calcium ranged from 10.07 to 11.57, with an average of 10.95. The average leach indexes for aluminum ranged from 12.00 to 16.00, with an average of 13.02. The average leach indexes for silicon ranged from 9.90 to 15.67, with an average of 11.45. Conservative diffusion modeling of calcium, aluminum and silicon using these leachability indexes resulted in estimates of mass fraction remaining at 1,000, 10,000, and 100,000 years. In the case of calcium, the species present in the largest quantities, the mass fraction remaining at 1,000, 10,000, and 100,000 years was 0.75, 0.37, 0.04. The time estimated to remove more than 50% of initial calcium ranges from 1,000 to 10,000 years, with the time estimated to remove more than 95% of calcium ranging from 10,000 to 100,000 years. These estimates are likely conservative primarily due to the presence of calcium, magnesium, carbonates, aluminates, and silicates that will coat the soil-grout surface and slow the leaching.

Although fracture density is demonstrated to be a sensitive parameter in mass release, seismic studies indicate that the seismic-induced stresses on a buried grout waste monolith in the vicinity of the SDA are low with respect to measured tensile strengths of the grout material. As a result, it is concluded that the monolith will not crack even under the largest anticipated peak ground acceleration of 0.32. Furthermore, it has been shown for shallow buried structures, that any seismic-induced forces that would be experienced are directed away from the monolith's bottom surface, where primary contaminant release takes place. However, analysis of thermal stresses envisioned under potential freezing and thawing of an uncovered monolith indicate that enough thermal strain would exist to cause cracking in the monolith for each of the five grouts evaluated.

Evaluating the chemical buffering properties of the grouted waste showed that the solubility of the majority of COPCs in SDA waste would be largely unaffected by grouting. Grouting may marginally increase the solubility of a small subset of modeled COPCs (i.e., actinium, americium, niobium, and lead). Six of the COPCs showed that grouting would result in decreased solubility (i.e., neptunium, protactinium, plutonium, strontium, uranium, and technetium). Of these six species, all but strontium showed a strong sensitivity of solubility to Eh conditions. Consequently, engineering grouts to ensure a moderately to highly reducing environment may be very successful in minimizing the solubility of neptunium, protactinium, plutonium, uranium, and technetium.

Numerical modeling indicated that nine COPCs were completely released over the 10,000 years simulated. These were Tc-99, nitrates, Cs-137, Pb-210, Cl-36, I-129, Ac-227, Am-241, and methylene chloride. Eight COPCs were shown to have released less than 5% of their total mass within 10,000 years: U-233, U-234, U-235, U-236, U-238, Pu-239, Pu-240, and Np-237. The remaining COPCs (i.e., C-14, Nb-94, carbon tetrachloride, and tetrachloroethylene) showed percent releases over 10,000 years of 71%, 30.4%, 11.4%, and 17.1%, respectively.

Parameter sensitivity analysis indicated that mass release from the monolith was relatively insensitive to infiltration and material permeability. However, these parameters did influence the moisture content of the monolith over the simulated duration. As a result, the monolith retained much (i.e., approximately 99.8 %) of the initial moisture at the end of 10,000 years. The parameters having the greatest effect on mass release from the monolith are the distribution coefficient and the fracture density.

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## **Appendix A**

### **Tabular and Graphical Mass Release Data for Contaminants of Potential Concern**



## Appendix A

### Tabular and Graphical Mass Release Data for Contaminants of Potential Concern

Table A-1. Ac-227.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	2.15E-02	2.15E-02	2.15E-02	0.000%	0.000%	0.000%
5.000E-01	2.13E-02	2.13E-02	2.13E-02	0.811%	0.808%	0.795%
1.001E+00	2.12E-02	2.12E-02	2.12E-02	1.596%	1.593%	1.583%
5.003E+00	1.99E-02	1.99E-02	1.99E-02	7.608%	7.605%	7.615%
1.001E+01	1.84E-02	1.84E-02	1.84E-02	14.519%	14.517%	14.570%
2.502E+01	1.41E-02	1.45E-02	1.45E-02	34.490%	32.351%	32.449%
5.003E+01	9.59E-03	9.90E-03	9.87E-03	55.394%	53.938%	54.067%
7.505E+01	6.68E-03	6.89E-03	6.87E-03	68.937%	67.923%	68.052%
1.001E+02	4.78E-03	4.93E-03	4.91E-03	77.781%	77.056%	77.173%
1.500E+02	2.66E-03	2.75E-03	2.73E-03	87.618%	87.213%	87.300%
2.000E+02	1.48E-03	1.53E-03	1.52E-03	93.104%	92.878%	92.939%
5.003E+02	7.92E-05	8.18E-05	4.47E-05	99.631%	99.619%	99.792%
1.001E+03	3.06E-05	7.00E-07	3.78E-07	99.858%	99.997%	99.998%
2.001E+03	4.15E-06	3.08E-09	—	99.981%	100.000%	100.000%
3.002E+03	3.02E-07	5.36E-11	—	99.999%	—	—
4.002E+03	2.86E-08	6.92E-13	—	100.000%	—	—

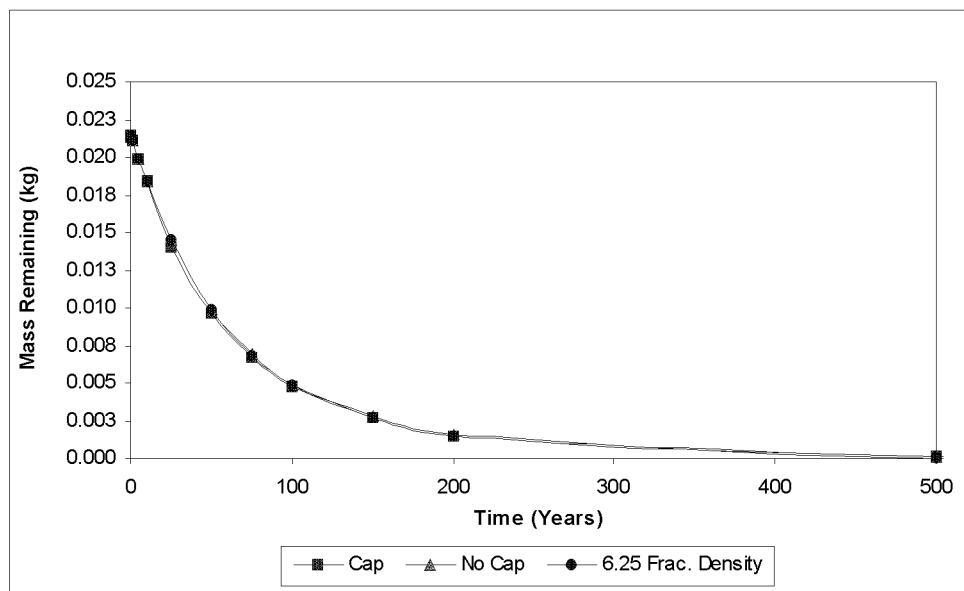


Figure A-1. Time release of Ac-227 from monolith, cap, no cap, and 6.25 fracture density.

Table A-2. Am-241.

Time Years	Mass Remaining			Mass Released		
	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	1.24E+00	1.24E+00	1.24E+00	0.000%	0.000%	0.00%
5.000E-01	1.24E+00	1.24E+00	1.23E+00	0.041%	0.041%	0.79%
1.001E+00	1.24E+00	1.24E+00	1.22E+00	0.081%	0.081%	1.58%
5.003E+00	1.23E+00	1.23E+00	1.14E+00	0.400%	0.400%	7.61%
1.001E+01	1.24E+00	1.23E+00	1.06E+00	0.081%	0.798%	14.59%
2.502E+01	1.21E+00	1.21E+00	8.37E-01	1.981%	1.981%	32.47%
5.003E+01	1.19E+00	1.19E+00	5.69E-01	3.921%	3.921%	54.08%
7.505E+01	1.17E+00	1.17E+00	3.96E-01	5.816%	5.816%	68.06%
1.001E+02	1.14E+00	1.14E+00	2.83E-01	7.665%	7.665%	77.18%
1.500E+02	1.10E+00	1.10E+00	1.57E-01	11.214%	11.214%	87.304%
2.000E+02	1.06E+00	1.06E+00	8.75E-02	14.630%	14.630%	92.941%
5.003E+02	8.36E-01	8.36E-01	2.58E-03	32.556%	32.556%	99.792%
1.001E+03	5.68E-01	5.68E-01	5.66E-05	54.120%	54.120%	99.995%
2.001E+03	2.81E-01	2.81E-01	—	77.321%	77.321%	100.000%
3.002E+03	1.48E-01	1.48E-01	—	88.088%	88.088%	—
4.002E+03	7.55E-02	7.55E-02	—	93.907%	93.907%	—
5.003E+03	4.19E-02	4.19E-02	—	96.618%	96.618%	—
6.004E+03	2.33E-02	2.33E-02	—	98.123%	98.123%	—
7.004E+03	1.29E-02	1.29E-02	—	98.958%	98.958%	—
8.005E+03	7.16E-03	7.16E-03	—	99.422%	99.422%	—
9.006E+03	3.98E-03	3.98E-03	—	99.679%	99.679%	—

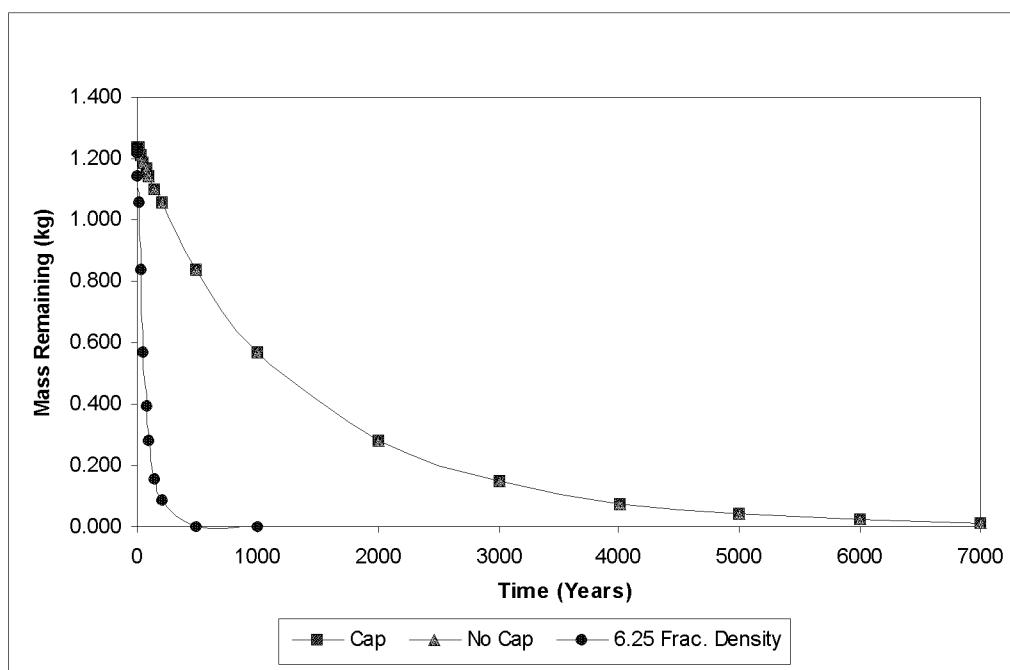


Figure A-2. Time release of Am-241 from monolith, cap, no cap, and 6.25 fracture density.

Table A-3. C-14.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	2.011E+00	2.011E+00	2.01E+00	0.000%	0.000%	0.000%
5.000E-01	2.011E+00	2.011E+00	2.01E+00	0.003%	0.003%	0.032%
1.001E+00	2.011E+00	2.011E+00	2.01E+00	0.006%	0.006%	0.064%
5.003E+00	2.010E+00	2.010E+00	2.00E+00	0.030%	0.030%	0.321%
1.001E+01	2.010E+00	2.010E+00	2.00E+00	0.061%	0.061%	0.645%
5.003E+01	2.004E+00	2.005E+00	1.95E+00	0.324%	0.315%	3.203%
1.001E+02	1.998E+00	1.998E+00	1.89E+00	0.660%	0.658%	6.243%
5.003E+02	1.934E+00	1.932E+00	1.48E+00	3.824%	3.915%	26.605%
1.001E+03	1.840E+00	1.835E+00	1.09E+00	8.486%	8.749%	45.675%
2.001E+03	1.639E+00	1.626E+00	6.18E-01	18.505%	19.132%	69.258%
3.002E+03	1.447E+00	1.429E+00	3.63E-01	28.027%	28.949%	81.957%
4.002E+03	1.271E+00	1.248E+00	2.04E-01	36.788%	37.932%	89.871%
5.003E+03	1.118E+00	1.092E+00	1.14E-01	44.419%	45.704%	94.321%
6.004E+03	9.817E-01	9.541E-01	6.33E-02	51.181%	52.554%	96.853%
7.004E+03	8.617E-01	8.332E-01	3.60E-02	57.147%	58.565%	98.210%
8.005E+03	7.560E-01	7.273E-01	2.02E-02	62.402%	63.831%	98.995%
9.006E+03	6.632E-01	6.348E-01	1.251E-02	67.017%	68.432%	99.378%
1.001E+04	5.817E-01	5.539E-01	6.948E-03	71.070%	72.452%	99.655%

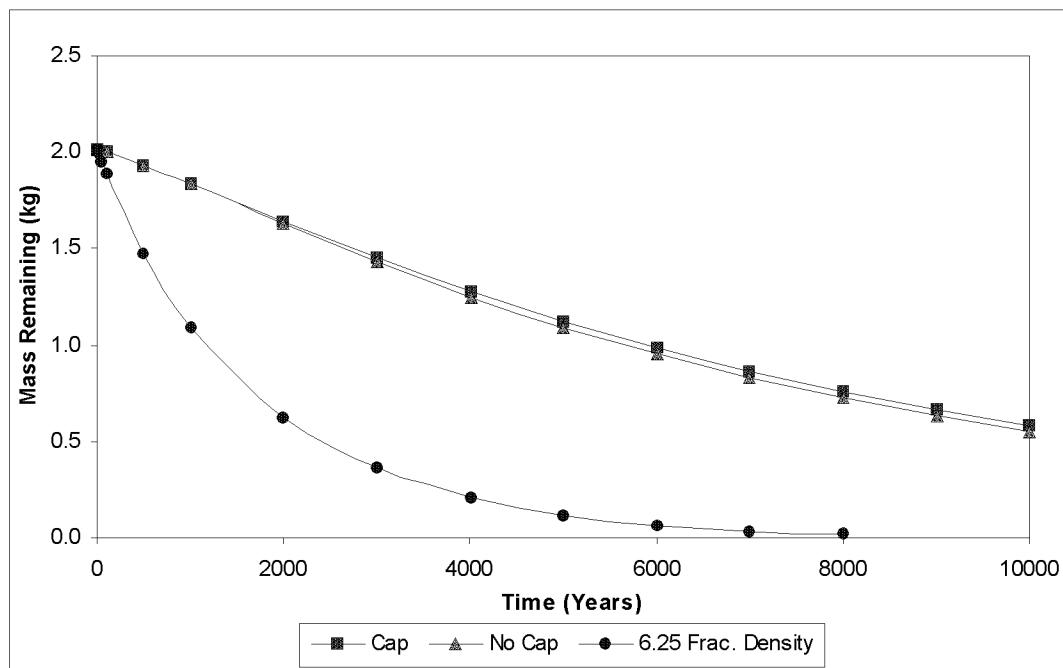


Figure A-3. Time release of C-14 from monolith, cap, no cap, and 6.25 fracture density.

Table A-4. Cs-137.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	3.87E+01	3.87E+01	3.870E+01	0.00%	0.00%	0.000%
5.000E-01	3.85E+01	3.85E+01	3.820E+01	0.57%	0.57%	1.281%
1.001E+00	3.82E+01	3.82E+01	3.771E+01	1.14%	1.14%	2.542%
5.003E+00	3.65E+01	3.65E+01	3.410E+01	5.55%	5.55%	11.885%
1.001E+01	3.45E+01	3.45E+01	3.011E+01	10.74%	10.74%	22.178%
5.003E+01	2.20E+01	2.20E+01	1.144E+01	43.09%	43.09%	70.445%
1.001E+02	1.31E+01	1.31E+01	4.140E+00	66.20%	66.20%	89.300%
2.000E+02	5.27E+00	5.27E+00	8.41E-01	86.38%	86.38%	97.83%
3.002E+02	2.12E+00	2.12E+00	1.72E-01	94.52%	94.52%	99.56%
4.003E+02	8.52E-01	8.52E-01	3.55E-02	97.80%	97.80%	99.91%
5.003E+02	3.43E-01	3.42E-01	7.373E-03	99.11%	99.11%	99.981%
1.001E+03	7.36E-03	7.36E-03	1.707E-05	99.98%	99.98%	100.000%
2.001E+03	7.02E-05	7.00E-05	—	100.00%	100.00%	—

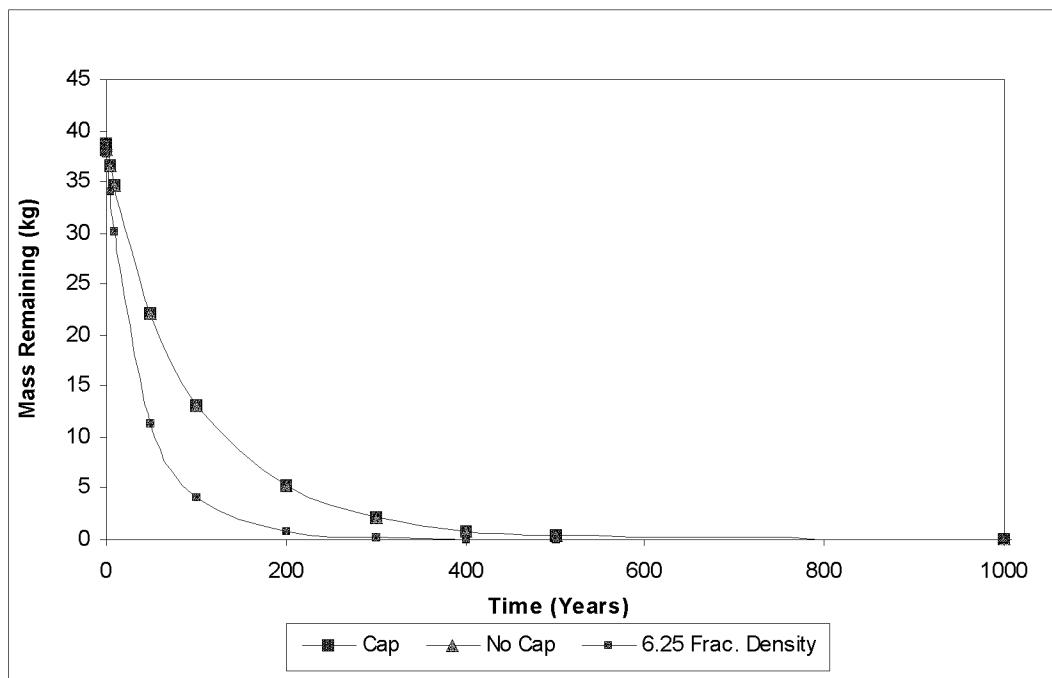


Figure A-4. Time release of Cs-137 from monolith, cap, no cap, and 6.25 fracture density.

Table A-5. Cl-36.

Time Years	Mass Remaining			Mass Released		
	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	1.43E-01	1.43E-01	1.43E-01	0.00%	0.00%	0.000%
5.000E-01	1.43E-01	1.43E-01	1.40E-01	0.01%	0.01%	2.422%
1.001E+00	1.43E-01	1.43E-01	1.36E-01	0.03%	0.03%	4.730%
5.003E+00	1.42E-01	1.42E-01	1.13E-01	0.64%	0.65%	20.678%
1.001E+01	1.40E-01	1.40E-01	9.09E-02	2.14%	2.15%	36.469%
5.003E+01	1.13E-01	1.12E-01	1.54E-02	20.74%	22.00%	89.248%
1.001E+02	8.34E-02	8.02E-02	2.67E-03	41.66%	43.94%	98.135%
2.000E+02	4.70E-02	4.36E-02	2.23E-04	67.14%	69.50%	99.84%
3.002E+02	2.64E-02	2.37E-02	1.86E-05	81.53%	83.43%	99.99%
4.003E+02	1.49E-02	1.29E-02	1.55E-06	89.61%	91.00%	100.00%
5.003E+02	8.35E-03	7.00E-03	—	94.16%	95.11%	—
1.001E+03	1.08E-03	4.74E-04	—	99.24%	99.67%	—
2.001E+03	1.26E-04	1.32E-05	—	99.91%	99.99%	—
3.002E+03	2.00E-05	8.11E-07	—	99.99%	100.00%	—
4.00E+03	3.99E-06	—	—	100.00%	—	—

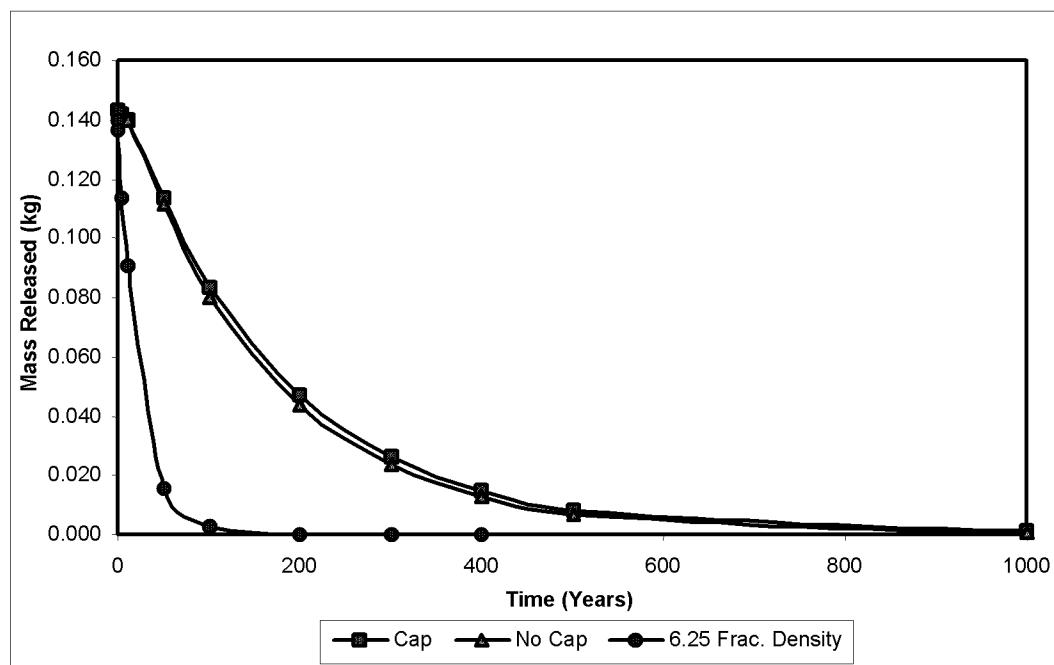


Figure A-5. Time release of Cl-36 from monolith, cap, no cap, and 6.25 fracture density.

Table A-6. I-129.

Time Years	Mass Remaining			Mass Released		
	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	2.31E+00	2.31E+00	2.31E+00	0.00%	0.00%	0.000%
5.000E-01	2.31E+00	2.31E+00	2.30E+00	0.00%	0.00%	0.565%
1.001E+00	2.31E+00	2.31E+00	2.29E+00	0.00%	0.00%	1.126%
5.003E+00	2.31E+00	2.31E+00	2.19E+00	0.04%	0.04%	5.417%
1.001E+01	2.31E+00	2.31E+00	2.07E+00	0.15%	0.15%	10.400%
5.003E+01	2.26E+00	2.25E+00	1.36E+00	2.46%	2.70%	41.294%
1.001E+02	2.14E+00	2.12E+00	8.23E-01	7.55%	8.27%	64.428%
2.000E+02	1.87E+00	1.84E+00	3.38E-01	19.03%	20.47%	85.38%
3.002E+02	1.62E+00	1.58E+00	1.38E-01	29.82%	31.77%	94.02%
4.003E+02	1.40E+00	1.35E+00	5.65E-02	39.36%	41.65%	97.558%
5.003E+02	1.21E+00	1.15E+00	2.31E-02	47.66%	50.15%	99.002%
1.001E+03	5.93E-01	5.38E-01	5.27E-04	74.36%	76.72%	99.977%
2.001E+03	1.74E-01	1.47E-01	5.309E-06	92.47%	93.63%	100.000%
3.002E+03	5.98E-02	4.78E-02	—	97.41%	97.93%	—
4.002E+03	1.93E-02	1.45E-02	—	99.17%	99.37%	—
5.003E+03	7.61E-03	5.49E-03	—	99.67%	99.76%	—
6.004E+03	3.00E-03	2.07E-03	—	99.87%	99.91%	—
7.004E+03	1.18E-03	7.84E-04	—	99.95%	99.97%	—
8.005E+03	4.67E-04	2.96E-04	—	99.98%	99.99%	—
9.006E+03	4.67E-04	1.12E-04	—	100.00%	100.00%	—

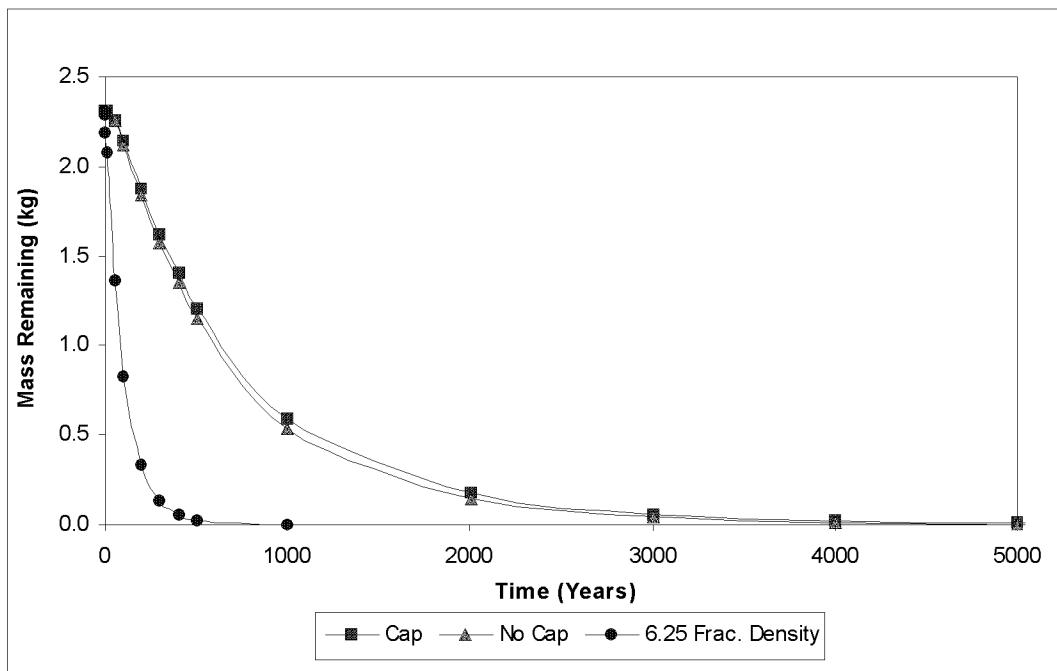


Figure A-6. Time release of I-129 from monolith, cap, no cap, and 6.25 fracture density.

Table A-7. Pb-210.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	1.18E-03	1.18E-03	1.19E-03	0.00%	0.00%	0.00%
5.000E-01	1.17E-03	1.18E-03	1.18E-03	0.88%	0.71%	0.78%
1.001E+00	1.17E-03	1.17E-03	1.17E-03	1.65%	1.48%	1.55%
5.003E+00	1.10E-03	1.10E-03	1.10E-03	7.52%	7.36%	7.46%
1.001E+01	1.02E-03	1.02E-03	1.02E-03	14.28%	14.13%	14.32%
5.003E+01	5.38E-04	5.56E-04	5.51E-04	54.59%	53.06%	53.54%
1.001E+02	2.72E-04	2.81E-04	2.77E-04	77.05%	76.28%	76.62%
2.000E+02	8.62E-05	8.62E-05	8.72E-05	92.72%	92.48%	92.64%
5.003E+02	4.86E-06	5.02E-06	2.71E-06	99.59%	99.58%	99.77%
1.001E+03	1.90E-06	4.62E-08	2.44E-08	99.84%	100.00%	100.00%
2.001E+03	2.64E-07	—	—	99.98%	—	—
3.002E+03	1.96E-08	—	—	100.00%	—	—

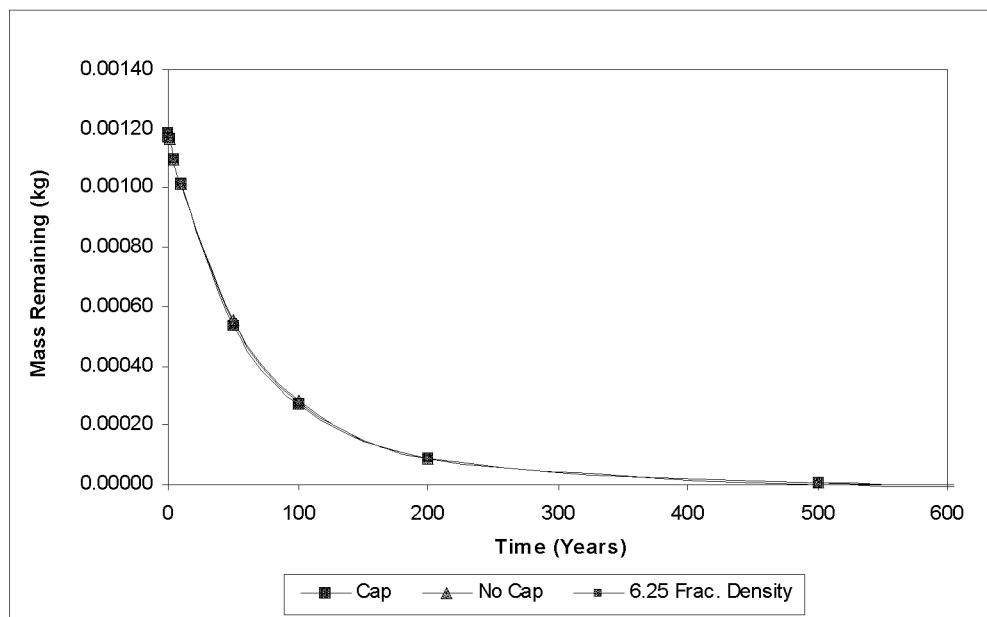


Figure A-7. Time release of Pb-210 from monolith, cap, no cap, and 6.25 fracture density.

Table A-8. Np-237.

Time Years	Mass Remaining			Mass Released		
	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	4.12E+00	4.12E+00	4.12E+00	0.000%	0.000%	0.000%
5.000E-01	4.12E+00	4.12E+00	4.12E+00	0.000%	0.000%	0.001%
1.001E+00	4.12E+00	4.12E+00	4.12E+00	0.000%	0.000%	0.003%
5.003E+00	4.12E+00	4.12E+00	4.12E+00	0.000%	0.000%	0.015%
1.001E+01	4.12E+00	4.12E+00	4.12E+00	0.000%	0.001%	0.029%
2.502E+01	4.12E+00	4.12E+00	4.12E+00	0.001%	0.001%	0.074%
5.003E+01	4.12E+00	4.12E+00	4.12E+00	0.002%	0.002%	0.151%
7.505E+01	4.12E+00	4.12E+00	4.11E+00	0.003%	0.003%	0.228%
1.001E+02	4.12E+00	4.12E+00	4.11E+00	0.004%	0.004%	0.306%
1.500E+02	4.12E+00	4.12E+00	4.10E+00	0.006%	0.006%	0.460%
2.000E+02	4.12E+00	4.12E+00	4.10E+00	0.008%	0.009%	0.615%
5.003E+02	4.12E+00	4.12E+00	4.06E+00	0.023%	0.025%	1.530%
1.001E+03	4.12E+00	4.12E+00	4.00E+00	0.053%	0.057%	3.012%
2.001E+03	4.12E+00	4.12E+00	3.88E+00	0.125%	0.137%	5.833%
3.002E+03	4.11E+00	4.11E+00	3.77E+00	0.215%	0.235%	8.510%
4.002E+03	4.11E+00	4.11E+00	3.67E+00	0.319%	0.348%	11.091%
5.003E+03	4.10E+00	4.10E+00	3.56E+00	0.438%	0.479%	13.586%
6.004E+03	4.10E+00	4.10E+00	3.46E+00	0.571%	0.623%	16.000%
7.004E+03	4.09E+00	4.09E+00	3.37E+00	0.716%	0.781%	18.336%
8.01E+03	4.09E+00	4.08E+00	3.27E+00	0.872%	0.950%	20.599%
9.01E+03	4.08E+00	4.08E+00	3.18E+00	1.039%	1.132%	22.800%
1.00E+04	4.07E+00	4.07E+00	3.09E+00	1.216%	1.324%	24.940%

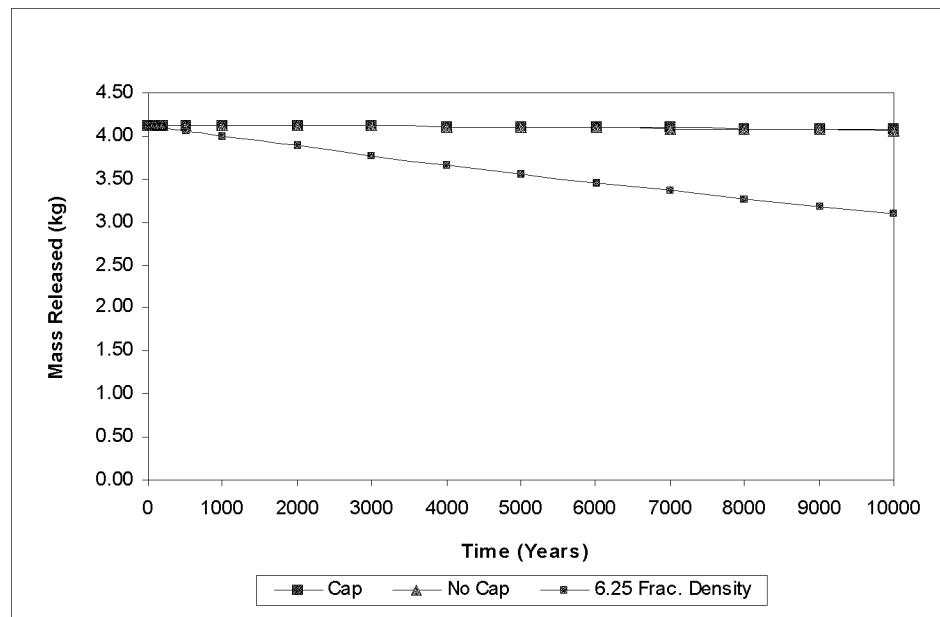


Figure A-8. Time release of Np-237 from monolith, cap, no cap, and 6.25 fracture density.

Table A-9. Nb-94.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	2.51E+00	2.51E+00	2.51E+00	0.000%	0.000%	0.000%
5.000E-01	2.51E+00	2.51E+00	2.51E+00	0.002%	0.002%	0.005%
1.001E+00	2.51E+00	2.51E+00	2.51E+00	0.004%	0.003%	0.009%
5.003E+00	2.51E+00	2.51E+00	2.50E+00	0.018%	0.017%	0.046%
1.001E+01	2.51E+00	2.51E+00	2.50E+00	0.035%	0.035%	0.092%
2.502E+01	2.50E+00	2.50E+00	2.50E+00	0.087%	0.087%	0.228%
5.003E+01	2.50E+00	2.50E+00	2.49E+00	0.173%	0.173%	0.455%
7.505E+01	2.50E+00	2.50E+00	2.49E+00	0.260%	0.260%	0.679%
1.001E+02	2.50E+00	2.50E+00	2.48E+00	0.346%	0.346%	0.902%
1.500E+02	2.49E+00	2.49E+00	2.47E+00	0.518%	0.518%	1.342%
2.000E+02	2.49E+00	2.49E+00	2.46E+00	0.690%	0.690%	1.778%
5.003E+02	2.46E+00	2.46E+00	2.40E+00	1.719%	1.719%	4.314%
1.001E+03	2.42E+00	2.42E+00	2.30E+00	3.414%	3.415%	8.291%
2.001E+03	2.34E+00	2.34E+00	2.12E+00	6.734%	6.741%	15.580%
3.002E+03	2.26E+00	2.26E+00	1.95E+00	9.968%	9.985%	22.207%
4.002E+03	2.18E+00	2.18E+00	1.79E+00	13.132%	13.164%	28.372%
5.003E+03	2.10E+00	2.10E+00	1.65E+00	16.204%	16.254%	34.078%
6.004E+03	2.02E+00	2.02E+00	1.52E+00	19.198%	19.267%	39.325%
7.004E+03	1.95E+00	1.95E+00	1.40E+00	22.111%	22.201%	44.203%
8.01E+03	1.88E+00	1.88E+00	1.29E+00	24.946%	25.057%	48.712%
9.01E+03	1.81E+00	1.81E+00	1.18E+00	27.699%	27.830%	52.895%
1.00E+04	1.74E+00	1.74E+00	1.08E+00	30.370%	30.523%	56.706%

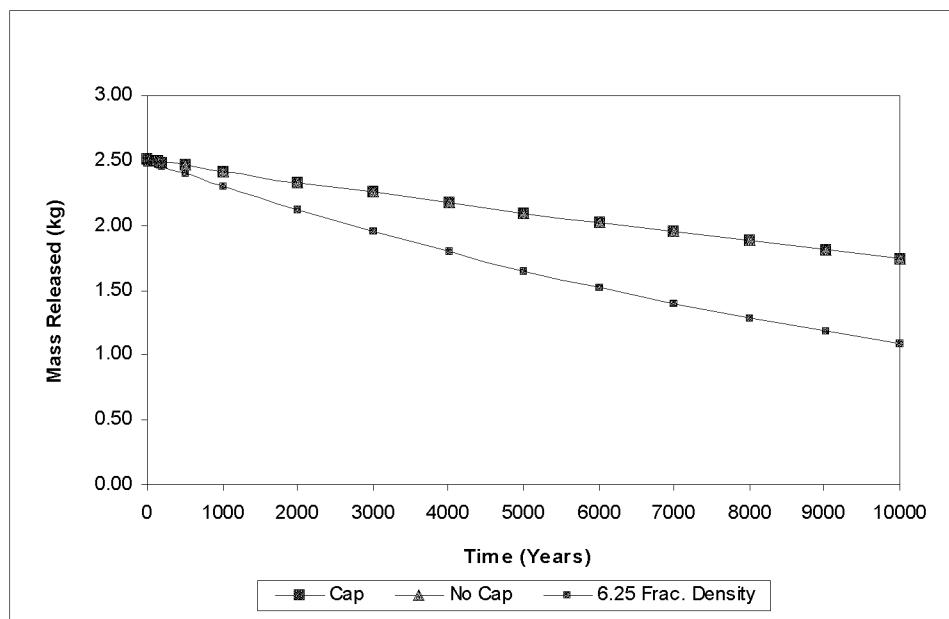


Figure A-9. Time release of Nb-94 from monolith, cap, no cap, and 6.25 fracture density.

Table A-10. Nitrate.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	1.63E+04	1.63E+04	1.634E+04	0.000%	0.000%	0.000%
5.000E-01	1.63E+04	1.63E+04	1.411E+04	0.236%	0.236%	13.671%
1.001E+00	1.62E+04	1.62E+04	1.230E+04	0.911%	0.911%	24.765%
5.003E+00	1.44E+04	1.44E+04	4.195E+03	12.164%	12.149%	74.333%
1.001E+01	1.20E+04	1.20E+04	1.030E+03	26.577%	26.508%	93.696%
5.003E+01	2.87E+03	2.75E+03	2.307E-01	82.441%	83.198%	99.999%
1.001E+02	6.70E+02	6.02E+02	1.245E-03	95.900%	96.315%	100.000%
5.003E+02	1.21E-01	8.44E-02	2.996E-13	99.999%	99.999%	100.000%
1.001E+03	—	1.28E-04	—	—	100.000%	—
2.001E+03	—	—	—	—	—	—
3.002E+03	—	—	—	—	—	—

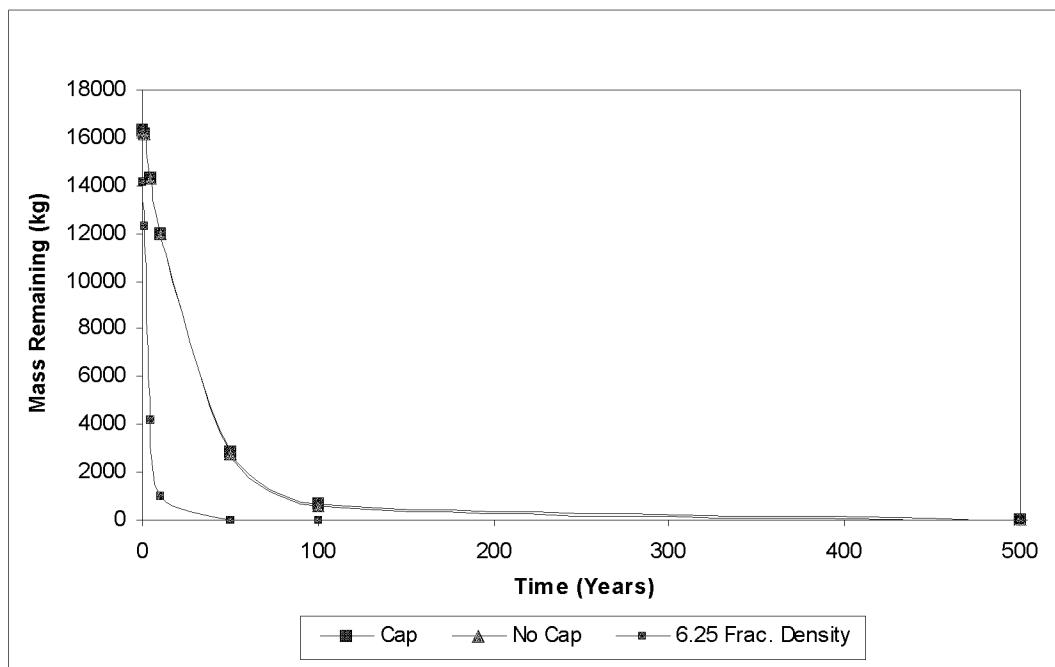


Figure A-10. Time release of nitrate from monolith, cap, no cap, and 6.25 fracture density.

Table A-11. Pu-239.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	2.554E-01	2.554E-01	N/A	0.00%	0.00%	N/A
5.000E-01	2.554E-01	2.554E-01	N/A	0.00%	0.01%	N/A
1.001E+00	2.554E-01	2.554E-01	N/A	0.00%	0.02%	N/A
5.003E+00	2.553E-01	2.553E-01	N/A	0.01%	0.03%	N/A
1.001E+01	2.553E-01	2.553E-01	N/A	0.03%	0.04%	N/A
5.003E+01	2.550E-01	2.550E-01	N/A	0.14%	0.16%	N/A
1.001E+02	2.546E-01	2.546E-01	N/A	0.29%	0.30%	N/A
5.003E+02	2.532E-01	2.543E-01	N/A	0.86%	0.44%	N/A
1.001E+03	2.496E-01	2.506E-01	N/A	2.27%	1.86%	N/A
2.001E+03	2.425E-01	2.436E-01	N/A	5.03%	4.63%	N/A
3.002E+03	2.357E-01	2.367E-01	N/A	7.70%	7.31%	N/A
4.002E+03	2.291E-01	2.301E-01	N/A	10.30%	9.92%	N/A
5.003E+03	2.227E-01	2.236E-01	N/A	12.81%	12.44%	N/A
6.004E+03	2.164E-01	2.174E-01	N/A	15.25%	14.89%	N/A
7.004E+03	2.104E-01	2.113E-01	N/A	17.62%	17.28%	N/A
8.005E+03	2.045E-01	2.053E-01	N/A	19.93%	19.60%	N/A
9.006E+03	1.987E-01	1.996E-01	N/A	22.17%	21.85%	N/A
1.001E+04	1.932E-01	1.940E-01	N/A	24.36%	24.04%	N/A

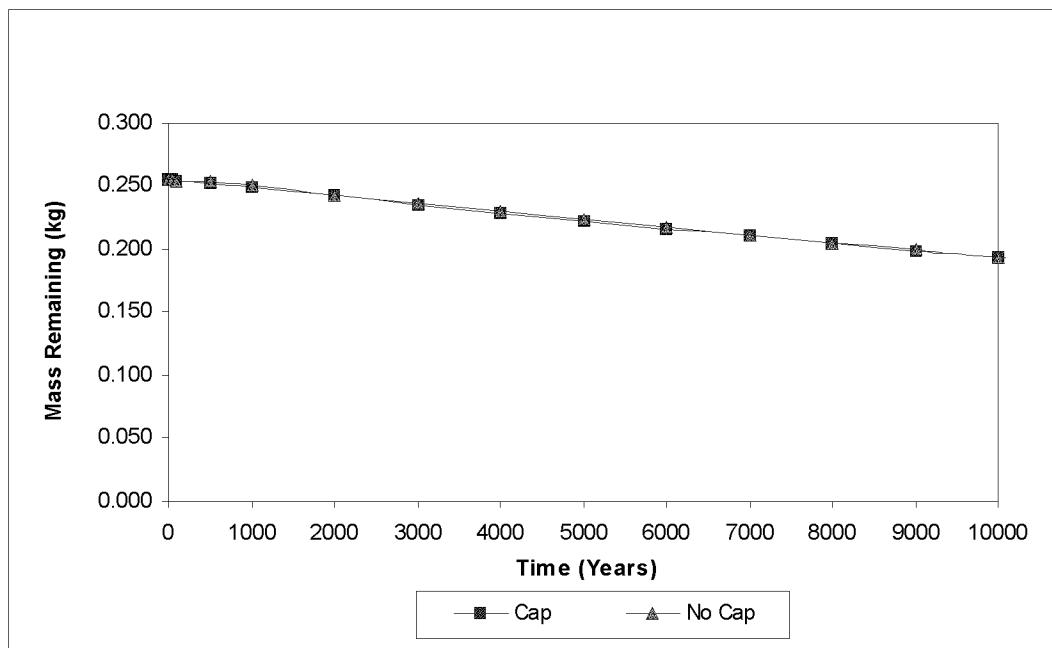


Figure A-11. Time release of Pu-239 from monolith, cap, no cap, and 6.25 fracture density.

Table A-12. Pu-240.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	2.55E-01	2.554E-01	2.55E-01	0.00%	0.00%	0.00%
5.000E-01	2.55E-01	2.554E-01	2.55E-01	0.01%	0.00%	0.00%
1.001E+00	2.55E-01	2.553E-01	2.55E-01	0.01%	0.01%	0.01%
5.003E+00	2.55E-01	2.553E-01	2.55E-01	0.03%	0.03%	0.03%
1.001E+01	2.55E-01	2.552E-01	2.55E-01	0.06%	0.06%	0.06%
5.003E+01	2.55E-01	2.546E-01	2.55E-01	0.28%	0.28%	0.32%
1.001E+02	2.54E-01	2.540E-01	2.54E-01	0.54%	0.54%	0.64%
5.003E+02	2.49E-01	2.487E-01	2.47E-01	2.62%	2.62%	3.15%
1.001E+03	2.42E-01	2.42E-01	2.40E-01	5.15%	5.15%	6.18%
2.001E+03	2.30E-01	2.299E-01	2.25E-01	9.99%	9.97%	11.88%
3.002E+03	2.18E-01	2.182E-01	2.12E-01	14.54%	14.53%	17.15%
4.002E+03	2.07E-01	2.071E-01	1.99E-01	18.88%	18.87%	22.14%
5.003E+03	1.97E-01	1.967E-01	1.87E-01	22.96%	22.95%	26.80%
6.004E+03	1.87E-01	1.869E-01	1.76E-01	26.83%	26.82%	31.17%
7.004E+03	1.77E-01	1.775E-01	1.65E-01	30.50%	30.49%	35.26%
8.005E+03	1.69E-01	1.686E-01	1.55E-01	33.99%	33.98%	39.147%
9.006E+03	1.60E-01	1.601E-01	1.46E-01	37.31%	37.30%	42.772%
1.001E+04	1.52E-01	1.520E-01	1.37E-01	40.46%	40.45%	46.182%

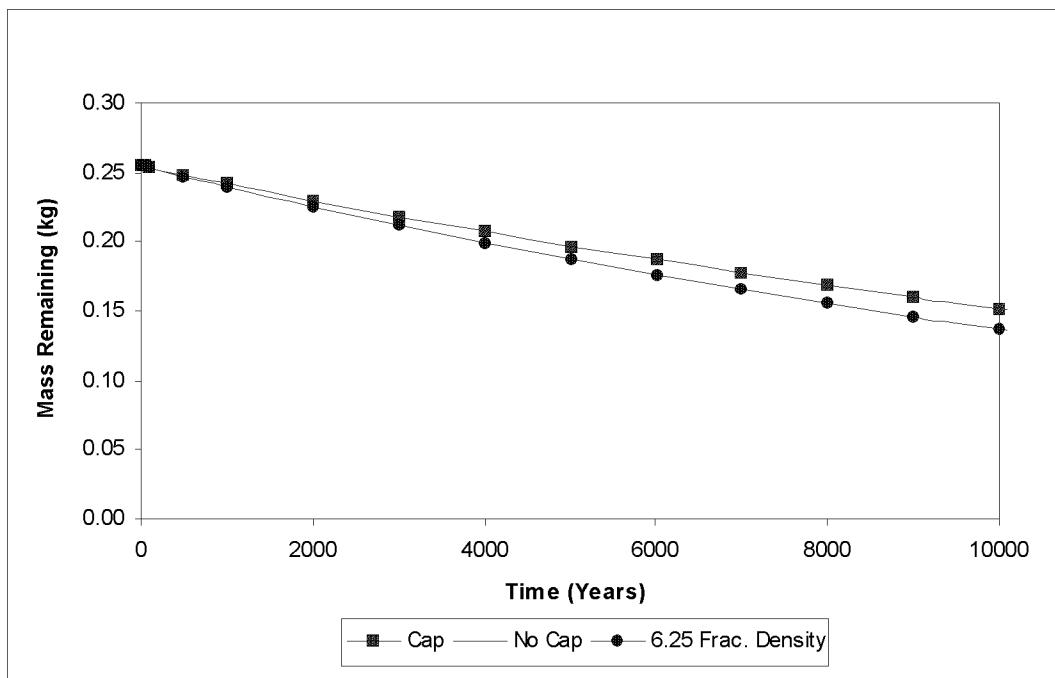


Figure A-12. Time release of Pu-240 from monolith, cap, no cap, and 6.25 fracture density.

Table A-13. Pa-231.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.0	2.60E+00	2.60E+00	2.60E+00	0.000%	0.000%	0.000%
0.5	2.60E+00	2.60E+00	2.60E+00	0.000%	0.001%	0.002%
1.0	2.60E+00	2.60E+00	2.60E+00	0.001%	0.002%	0.003%
5.0	2.60E+00	2.60E+00	2.60E+00	0.010%	0.011%	0.016%
10.0	2.60E+00	2.60E+00	2.60E+00	0.020%	0.021%	0.033%
50.0	2.60E+00	2.60E+00	2.60E+00	0.105%	0.106%	0.163%
100.1	2.60E+00	2.60E+00	2.60E+00	0.210%	0.211%	0.325%
500.3	2.58E+00	2.58E+00	2.56E+00	1.050%	1.051%	1.606%
1000.6	2.55E+00	2.55E+00	2.52E+00	2.089%	2.090%	3.173%
2001.3	2.50E+00	2.50E+00	2.44E+00	4.130%	4.131%	6.193%
3002.0	2.44E+00	2.44E+00	2.37E+00	6.123%	6.125%	9.099%
4002.4	2.39E+00	2.39E+00	2.29E+00	8.079%	8.081%	11.899%
5003.2	2.34E+00	2.34E+00	2.22E+00	9.987%	9.989%	14.612%
6003.9	2.29E+00	2.29E+00	2.16E+00	11.857%	11.860%	17.238%
7004.4	2.25E+00	2.25E+00	2.09E+00	13.688%	13.693%	19.775%
8005.5	2.20E+00	2.20E+00	2.03E+00	15.485%	15.490%	22.214%
9005.9	2.15E+00	2.15E+00	1.96E+00	17.245%	17.251%	24.572%
10006.7	2.11E+00	2.11E+00	1.90E+00	18.970%	18.978%	26.892%

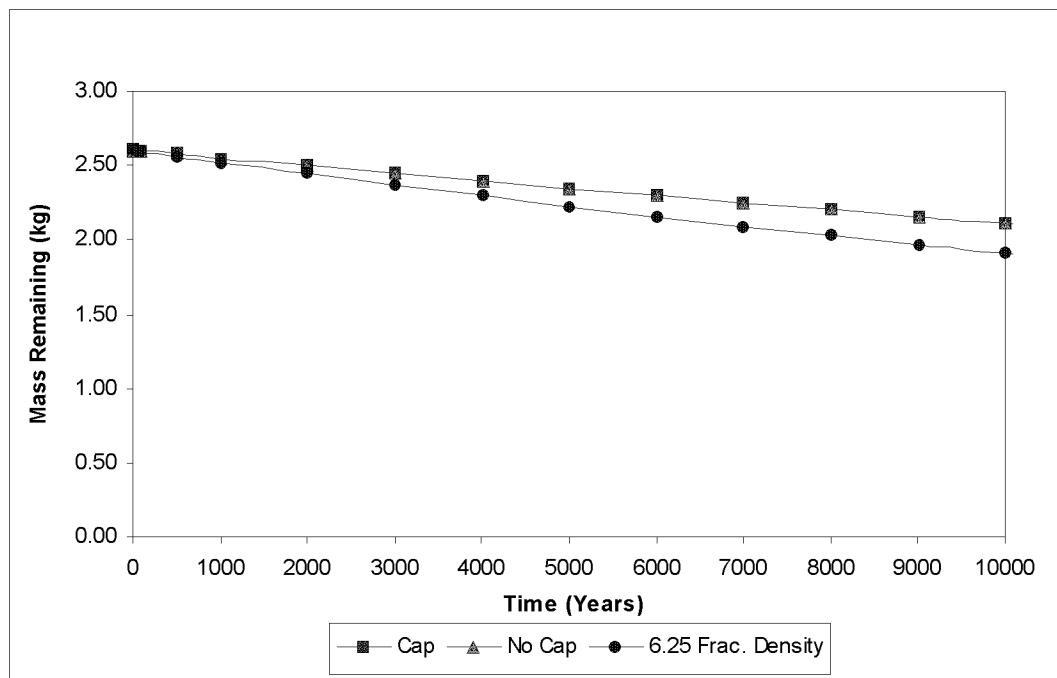


Figure A-13. Time release of Pa-231 from monolith, cap, no cap, and 6.25 fracture density.

Table A-14. R-226.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	6.66E-02	6.66E-02	6.66E-02	0.000%	0.00000%	0.000%
5.000E-01	6.66E-02	6.66E-02	6.66E-02	0.011%	0.01109%	0.068%
1.001E+00	6.66E-02	6.66E-02	6.65E-02	0.022%	0.02193%	0.136%
5.003E+00	6.66E-02	6.66E-02	6.62E-02	0.109%	0.10858%	0.665%
1.001E+01	6.65E-02	6.65E-02	6.58E-02	0.217%	0.21691%	1.306%
5.003E+01	6.59E-02	6.59E-02	6.27E-02	1.126%	1.08324%	5.882%
1.001E+02	6.52E-02	6.52E-02	5.96E-02	2.207%	2.16464%	10.618%
5.003E+02	5.95E-02	5.96E-02	4.38E-02	10.638%	10.60245%	34.264%
1.001E+03	5.31E-02	5.31E-02	3.37E-02	20.325%	20.30173%	49.446%
2.001E+03	4.24E-02	4.24E-02	2.36E-02	36.293%	36.30169%	64.550%
3.002E+03	3.42E-02	3.42E-02	1.75E-02	48.638%	48.67334%	73.686%
4.002E+03	2.75E-02	2.75E-02	1.34E-02	58.700%	58.75519%	79.903%
5.003E+03	2.24E-02	2.23E-02	1.02E-02	66.426%	66.49394%	84.634%
6.004E+03	1.82E-02	1.81E-02	7.89E-03	72.693%	72.76696%	88.155%
7.004E+03	1.48E-02	1.48E-02	6.10E-03	77.778%	77.85431%	90.846%
8.005E+03	1.21E-02	1.20E-02	4.76E-03	81.910%	81.98642%	92.855%
9.006E+03	9.82E-03	9.77E-03	3.69E-03	85.268%	85.34090%	94.455%
1.001E+04	8.00E-03	7.95E-03	3.04E-03	87.999%	88.06804%	95.432%

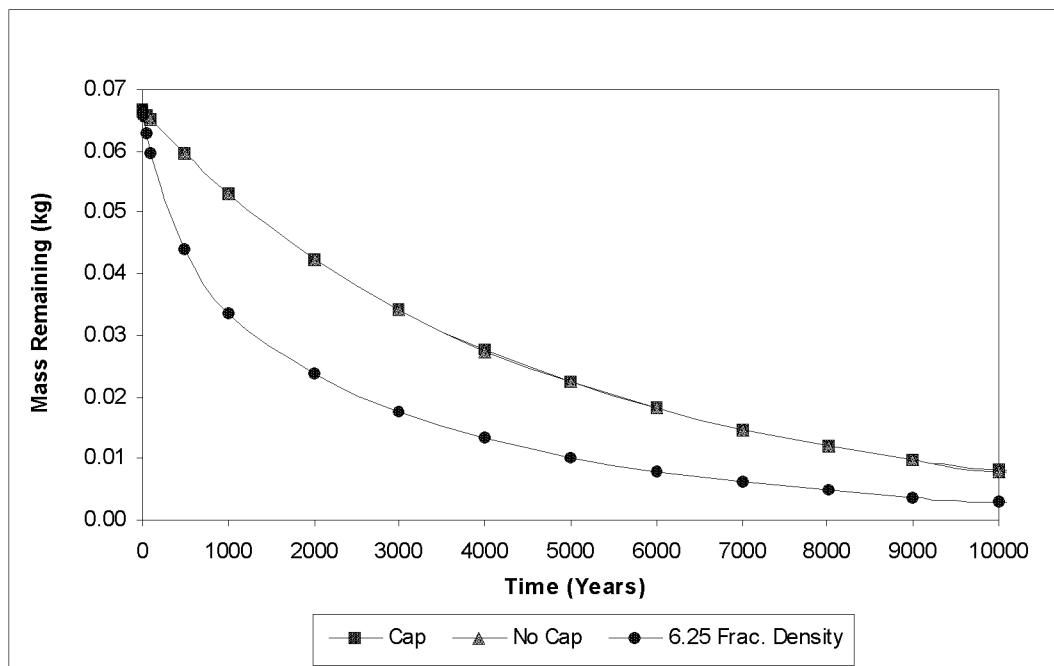


Figure A-14. Time release of R-226 from monolith, cap, no cap, and 6.25 fracture density.

Table A-15. Sr-90.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	3.94E-04	3.94E-04	3.94E-04	0.000%	0.000%	0.000%
5.000E-01	3.91E-04	3.91E-04	3.82E-04	0.598%	0.599%	2.847%
1.001E+00	3.89E-04	3.89E-04	3.72E-04	1.191%	1.193%	5.369%
5.003E+00	3.70E-04	3.70E-04	3.14E-04	5.862%	5.864%	20.248%
1.001E+01	3.48E-04	3.48E-04	2.63E-04	11.472%	11.474%	33.282%
5.003E+01	2.03E-04	2.08E-04	9.25E-05	48.319%	47.256%	76.505%
1.001E+02	1.10E-04	1.12E-04	3.38E-05	71.937%	71.566%	91.401%
2.001E+02	3.86E-05	3.87E-05	6.76E-06	90.20%	90.16%	98.30%
3.001E+02	1.35E-05	1.35E-05	1.54E-06	96.56%	96.57%	99.61%
4.001E+02	4.80E-06	4.75E-06	3.56E-07	98.78%	98.79%	99.91%
5.003E+02	2.86E-06	2.82E-06	8.27E-08	99.272%	99.282%	99.979%
1.001E+03	1.22E-06	3.93E-08	8.44E-10	99.691%	99.990%	100.000%
2.001E+03	1.87E-07	2.56E-10	—	99.952%	100.000%	—
3.002E+03	1.63E-08	5.92E-12	—	99.996%	—	—
4.002E+03	—	9.68E-14	—	100.000%	—	—

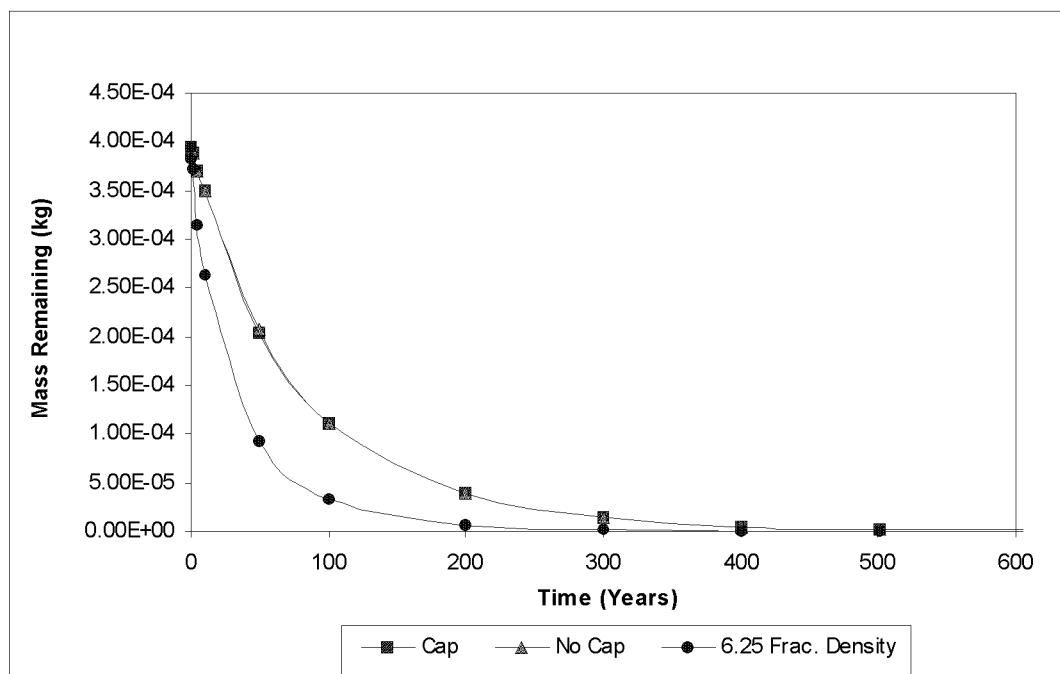


Figure A-15. Time release of Sr-90 from monolith, cap, no cap, and 6.25 fracture density.

Table A-16. Tc-99.

Time	Mass Remaining			Mass Released			
	Years	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	3.90E+01	3.899E+01	3.90E+01	3.90E+01	0.00%	0.00%	0.00%
5.000E-01	3.9E+01	3.869E+01	3.22E+01	3.22E+01	0.77%	0.77%	17.50%
1.001E+00	3.81E+01	3.807E+01	2.67E+01	2.67E+01	2.36%	2.35%	31.57%
5.003E+00	3.1E+01	3.100E+01	7.68E+00	7.68E+00	20.52%	20.48%	80.30%
1.001E+01	2.4E+01	2.373E+01	1.69E+00	1.69E+00	39.31%	39.13%	95.67%
2.502E+01	1.0E+01	1.055E+01	2.18E-02	2.18E-02	73.37%	72.94%	99.94%
5.003E+01	2.8E+00	2.921E+00	8.45E-05	8.45E-05	92.69%	92.51%	100.00%
1.001E+02	2.6E-02	4.045E-01	—	—	99.93%	98.96%	—
2.003E+02	2.6E-02	2.67E-02	—	—	99.93%	99.93%	—
2.503E+02	6.8E-03	6.844E-03	—	—	99.98%	99.98%	—
3.003E+02	1.8E-03	1.757E-03	—	—	100.00%	100.00%	—

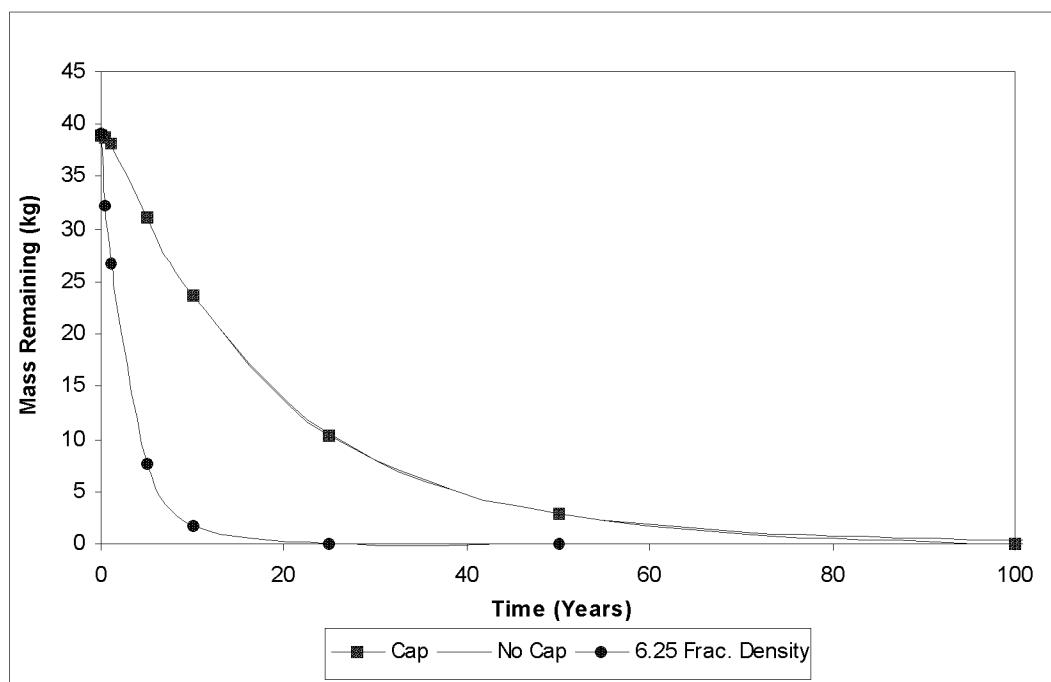


Figure A-16. Time release of Tc-99 from monolith, cap, no cap, and 6.25 fracture density.

Table A-17. U-233.

Time Years	Mass Remaining			Mass Released		
	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	4.01E-02	4.01E-02	4.01E-02	0.000%	0.000%	0.000%
5.000E-01	4.03E-02	3.98E-02	4.01E-02	-0.410%	0.616%	0.003%
1.001E+00	4.03E-02	3.98E-02	4.01E-02	-0.410%	0.616%	0.006%
5.003E+00	4.03E-02	3.98E-02	4.01E-02	-0.408%	0.618%	0.031%
1.001E+01	4.03E-02	3.98E-02	4.01E-02	-0.406%	0.620%	0.061%
5.003E+01	4.02E-02	3.98E-02	4.00E-02	-0.388%	0.637%	0.306%
1.001E+02	4.02E-02	3.98E-02	3.99E-02	-0.366%	0.659%	0.608%
5.003E+02	4.02E-02	3.98E-02	3.89E-02	-0.210%	0.814%	2.967%
1.001E+03	4.02E-02	3.97E-02	3.78E-02	-0.164%	1.049%	5.806%
2.001E+03	4.00E-02	3.95E-02	3.56E-02	0.231%	1.578%	11.174%
3.002E+03	3.98E-02	3.92E-02	3.36E-02	0.672%	2.177%	16.198%
4.002E+03	3.97E-02	3.90E-02	3.17E-02	1.022%	2.825%	20.933%
5.003E+03	3.94E-02	3.87E-02	2.99E-02	1.652%	3.527%	25.404%
6.004E+03	3.92E-02	3.84E-02	2.82E-02	2.323%	4.267%	29.630%
7.004E+03	3.89E-02	3.81E-02	2.69E-02	3.030%	5.037%	32.820%
8.005E+03	3.86E-02	3.78E-02	2.54E-02	3.768%	5.837%	36.646%
9.006E+03	3.83E-02	3.74E-02	2.40E-02	4.533%	6.659%	40.218%
1.001E+04	3.83E-02	3.71E-02	2.33E-02	4.533%	7.503%	41.954%

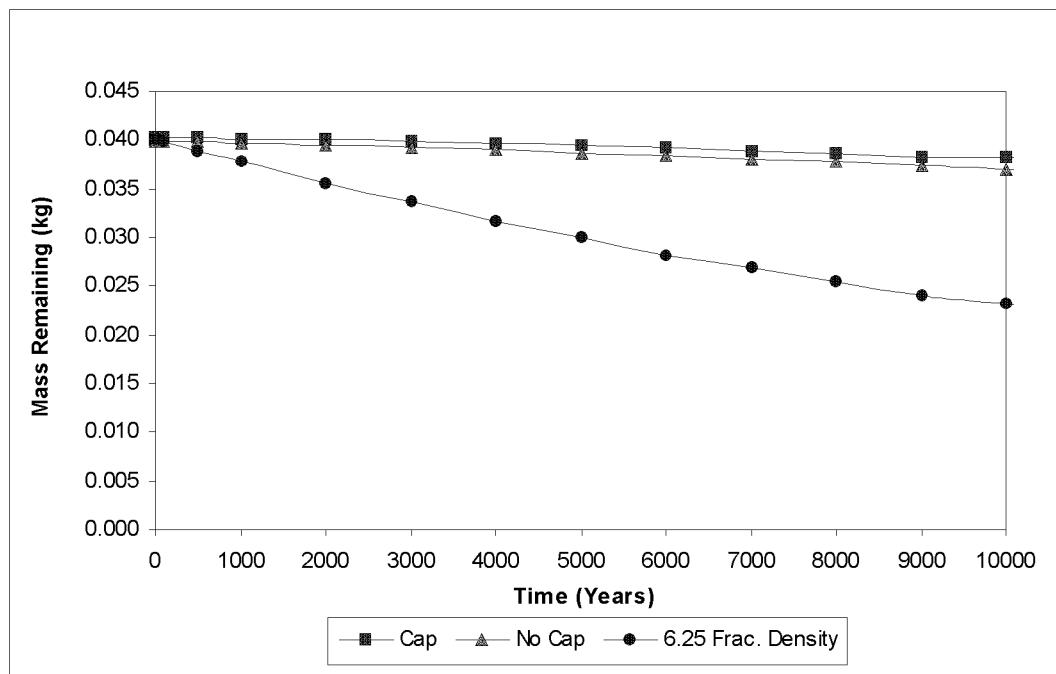


Figure A-17. Time release of U-233 from monolith, cap, no cap, and 6.25 fracture density.

Table A-18. U-234.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	4.02E-02	4.01E-02	4.01E-02	0.000%	0.000%	0.00%
5.000E-01	4.02E-02	4.01E-02	4.01E-02	0.000%	0.060%	0.00%
1.001E+00	4.02E-02	4.01E-02	4.01E-02	0.000%	0.061%	0.01%
5.003E+00	4.02E-02	4.01E-02	4.01E-02	0.000%	0.062%	0.03%
1.001E+01	4.02E-02	4.01E-02	4.01E-02	0.000%	0.063%	0.06%
5.003E+01	4.02E-02	4.01E-02	4.00E-02	0.000%	0.074%	0.30%
1.001E+02	4.02E-02	4.01E-02	3.99E-02	0.000%	0.089%	0.59%
5.003E+02	4.01E-02	4.00E-02	3.89E-02	0.070%	0.191%	2.89%
1.001E+03	3.99E-02	3.99E-02	3.81E-02	0.389%	0.350%	5.00%
2.001E+03	3.98E-02	3.98E-02	3.60E-02	0.649%	0.730%	10.15%
3.002E+03	3.96E-02	3.96E-02	3.41E-02	1.130%	1.183%	14.97%
4.002E+03	3.94E-02	3.94E-02	3.23E-02	1.654%	1.687%	19.55%
5.003E+03	3.92E-02	3.92E-02	3.05E-02	2.216%	2.248%	23.90%
6.004E+03	3.90E-02	3.89E-02	2.93E-02	2.812%	2.848%	27.01%
7.004E+03	3.87E-02	3.87E-02	2.81E-02	3.438%	3.483%	30.00%
8.005E+03	3.87E-02	3.84E-02	2.69E-02	3.438%	4.149%	32.87%
9.006E+03	3.87E-02	3.81E-02	2.62E-02	3.787%	4.841%	34.72%
1.001E+04	3.87E-02	3.79E-02	2.475E-02	3.787%	5.557%	38.272%

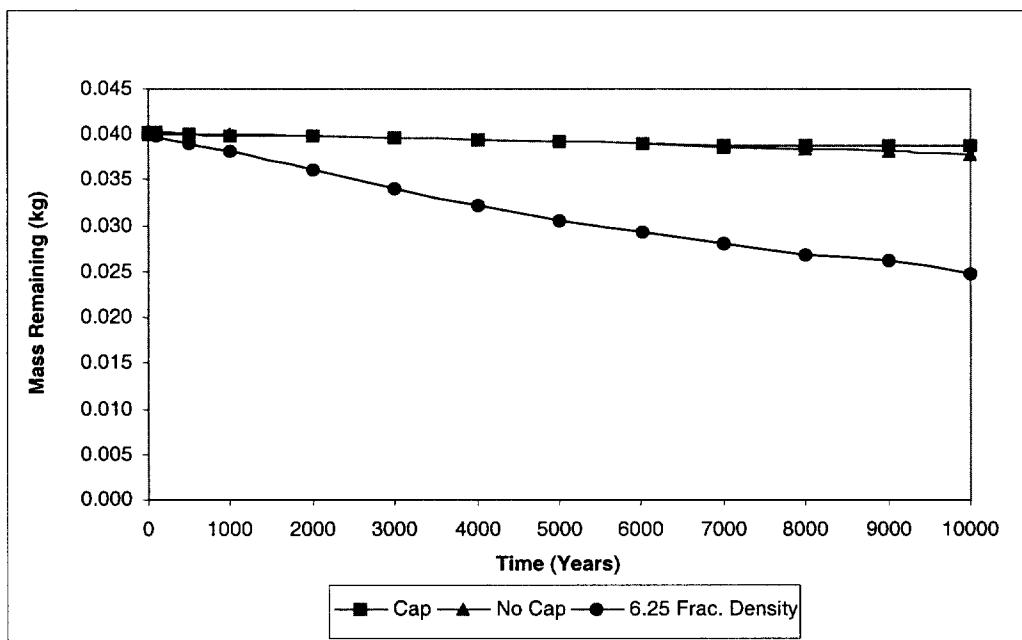


Figure A-18. Time release of U-234 from monolith, cap, no cap, and 6.25 fracture density.

Table A-19. U-235.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	4.01E-02	4.01E-02	4.01E-02	0.000%	0.000%	0.00%
5.000E-01	4.05E-02	3.99E-02	4.01E-02	0.000%	0.580%	0.00%
1.001E+00	4.05E-02	3.99E-02	4.01E-02	0.000%	0.580%	0.01%
5.003E+00	4.05E-02	3.99E-02	4.01E-02	0.000%	0.580%	0.03%
1.001E+01	4.05E-02	3.99E-02	4.01E-02	0.000%	0.580%	0.06%
5.003E+01	4.05E-02	3.99E-02	4.00E-02	0.000%	0.580%	0.28%
1.001E+02	4.05E-02	3.99E-02	3.99E-02	0.000%	0.580%	0.57%
5.003E+02	4.05E-02	3.99E-02	3.90E-02	0.000%	0.583%	2.76%
1.001E+03	4.05E-02	3.98E-02	3.81E-02	0.000%	0.602%	4.87%
2.001E+03	4.04E-02	3.98E-02	3.61E-02	0.000%	0.703%	9.91%
3.002E+03	4.04E-02	3.97E-02	3.42E-02	0.000%	0.878%	14.63%
4.002E+03	4.04E-02	3.96E-02	3.24E-02	0.000%	1.105%	19.11%
5.003E+03	4.03E-02	3.95E-02	3.07E-02	0.000%	1.394%	23.38%
6.004E+03	4.02E-02	3.94E-02	2.91E-02	0.000%	1.725%	27.41%
7.004E+03	4.01E-02	3.93E-02	2.76E-02	0.060%	2.094%	31.20%
8.005E+03	3.99E-02	3.91E-02	2.68E-02	0.391%	2.497%	33.05%
9.006E+03	3.98E-02	3.89E-02	2.54E-02	0.754%	2.930%	36.60%
1.001E+04	3.96E-02	3.87E-02	2.41E-02	1.148%	3.391%	39.93%

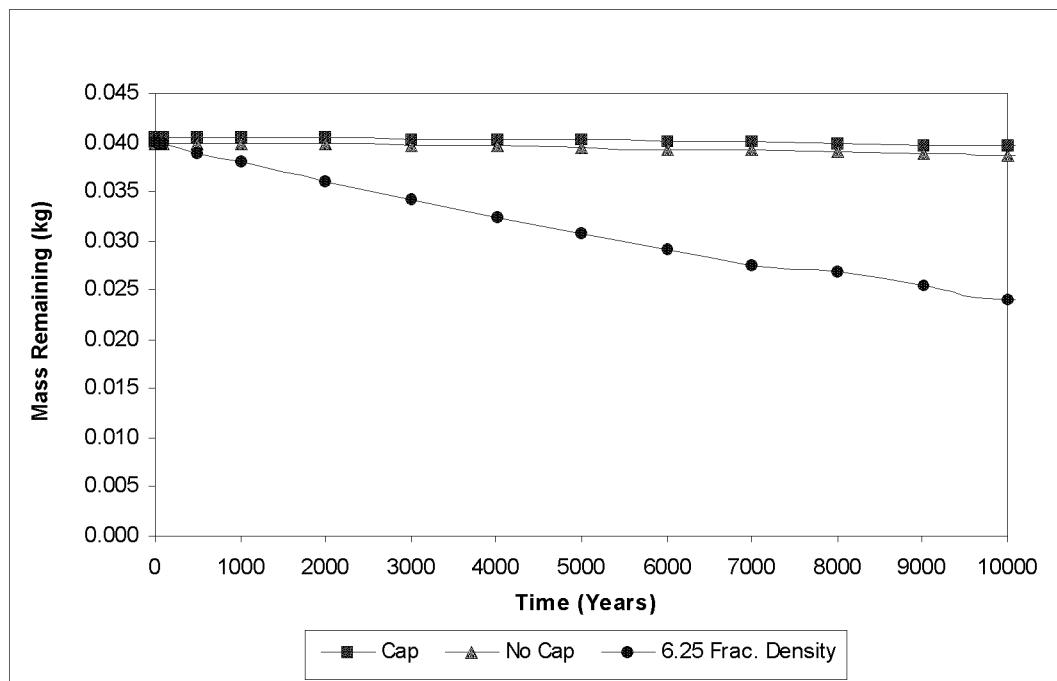


Figure A-19. Time release of U-235 from monolith, cap, no cap, and 6.25 fracture density.

Table A-20. U-236.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	4.01E-02	4.01E-02	4.01E-02	0.000%	0.000%	0.00%
5.000E-01	4.03E-02	4.00E-02	4.01E-02	0.000%	0.304%	0.00%
1.001E+00	4.03E-02	4.00E-02	4.01E-02	0.000%	0.304%	0.01%
5.003E+00	4.03E-02	4.00E-02	4.01E-02	0.000%	0.304%	0.03%
1.001E+01	4.03E-02	4.00E-02	4.01E-02	0.000%	0.304%	0.06%
5.003E+01	4.03E-02	4.00E-02	4.00E-02	0.000%	0.304%	0.28%
1.001E+02	4.03E-02	4.00E-02	3.99E-02	0.000%	0.304%	0.57%
5.003E+02	4.03E-02	4.00E-02	3.90E-02	0.000%	0.308%	2.76%
1.001E+03	4.03E-02	4.00E-02	3.81E-02	0.000%	0.327%	4.87%
2.001E+03	4.03E-02	3.99E-02	3.61E-02	0.000%	0.427%	9.91%
3.002E+03	4.02E-02	3.98E-02	3.42E-02	0.000%	0.603%	14.63%
4.002E+03	4.02E-02	3.98E-02	3.24E-02	0.000%	0.831%	19.11%
5.003E+03	4.01E-02	3.96E-02	3.07E-02	0.000%	1.120%	23.36%
6.004E+03	4.00E-02	3.95E-02	2.94E-02	0.212%	1.452%	26.58%
7.004E+03	3.99E-02	3.94E-02	—	0.504%	1.822%	—
8.005E+03	3.98E-02	3.92E-02	—	0.834%	2.226%	—
9.006E+03	3.96E-02	3.90E-02	—	1.196%	2.660%	—
1.001E+04	3.95E-02	3.88E-02	—	1.588%	3.123%	—

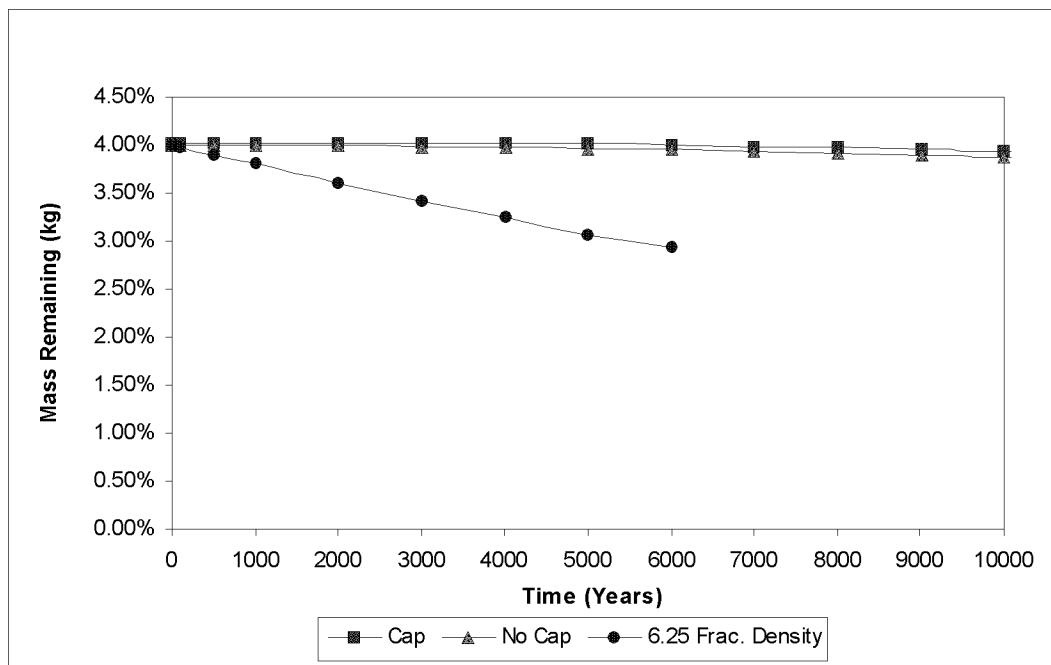


Figure A-20. Time release of U-236 from monolith, cap, no cap, and 6.25 fracture density.

Table A-21. U-238.

Time	Mass Remaining			Mass Released			
	Years	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+00	4.008E-02	4.014E-02	4.01E-02	0.00%	0.00%	0.00%	0.00%
5.000E-01	4.008E-02	4.014E-02	4.01E-02	0.00%	0.00%	0.00%	0.00%
1.001E+00	4.008E-02	4.014E-02	4.01E-02	0.00%	0.00%	0.00%	0.01%
5.003E+00	4.008E-02	4.014E-02	4.01E-02	0.00%	0.00%	0.00%	0.03%
1.001E+01	4.008E-02	4.014E-02	4.01E-02	0.00%	0.00%	0.00%	0.06%
5.003E+01	4.008E-02	4.014E-02	4.00E-02	0.00%	0.00%	0.00%	0.28%
1.001E+02	4.008E-02	4.014E-02	3.99E-02	0.00%	0.00%	0.00%	0.57%
5.003E+02	4.008E-02	4.013E-02	3.90E-02	0.00%	0.00%	0.00%	2.76%
1.001E+03	4.008E-02	4.007E-02	3.81E-02	0.01%	0.01%	0.01%	4.87%
2.001E+03	4.006E-02	4.002E-02	3.65E-02	0.05%	0.05%	0.05%	8.94%
3.002E+03	4.003E-02	3.994E-02	3.46E-02	0.15%	0.15%	0.15%	13.75%
4.002E+03	3.999E-02	3.984E-02	3.31E-02	0.24%	0.24%	0.24%	17.41%
5.003E+03	3.991E-02	3.972E-02	3.17E-02	0.44%	0.44%	0.44%	20.92%
6.004E+03	3.981E-02	3.958E-02	3.00E-02	0.69%	0.69%	0.69%	25.09%
7.004E+03	3.969E-02	3.942E-02	2.88E-02	0.98%	0.98%	0.98%	28.27%
8.005E+03	3.956E-02	3.924E-02	2.75E-02	1.31%	1.31%	1.31%	31.330%
9.006E+03	3.941E-02	3.906E-02	2.64E-02	1.67%	1.67%	1.67%	34.256%
1.001E+04	3.926E-02	3.886E-02	2.55E-02	2.06%	2.06%	2.06%	36.413%

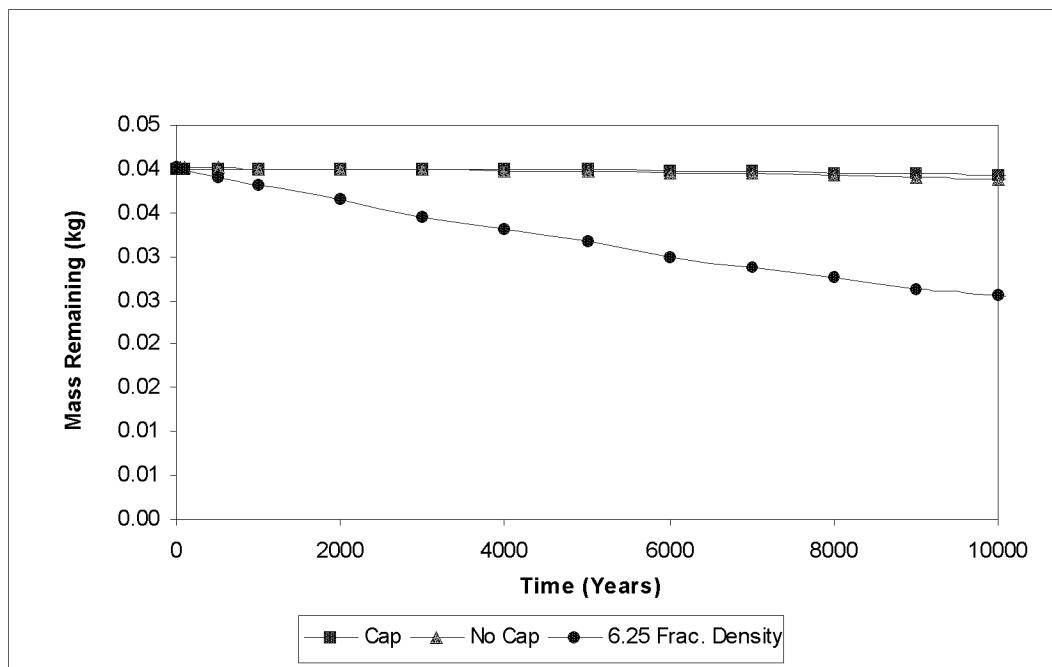


Figure A-21. Time release of U-238 from monolith, cap, no cap, and 6.25 fracture density.

Table A-22. Methylene chloride.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	4.830E+02	4.830E+02	4.83E+02	0.000%	0.000%	0.000%
2.500E-01	4.827E+02	4.827E+02	4.48E+02	0.056%	0.056%	7.337%
5.000E-01	4.819E+02	4.819E+02	4.17E+02	0.225%	0.225%	13.630%
1.001E+00	4.787E+02	4.787E+02	3.63E+02	0.891%	0.891%	24.831%
5.003E+00	4.243E+02	4.244E+02	1.29E+02	12.148%	12.133%	73.234%
1.001E+01	3.551E+02	3.554E+02	3.92E+01	26.486%	26.417%	91.876%
1.201E+01	3.296E+02	3.301E+02	2.44E+01	31.751%	31.664%	94.948%
1.501E+01	2.954E+02	2.958E+02	1.28E+01	38.849%	38.754%	97.355%
1.601E+01	2.844E+02	2.848E+02	9.81E+00	41.128%	41.033%	97.970%
1.801E+01	2.639E+02	2.643E+02	6.109E+00	45.354%	45.271%	98.735%
2.001E+01	2.450E+02	2.453E+02	3.808E+00	49.268%	49.214%	99.212%
2.502E+01	2.046E+02	2.041E+02	1.326E+00	57.651%	57.740%	99.725%
3.002E+01	1.705E+02	1.691E+02	4.353E-01	64.710%	64.985%	99.910%
3.502E+01	1.432E+02	1.410E+02	1.741E-01	70.361%	70.818%	99.964%
4.003E+01	1.203E+02	1.173E+02	6.967E-02	75.102%	75.705%	99.986%
4.503E+01	1.010E+02	9.763E+01	2.790E-02	79.086%	79.787%	99.994%
5.003E+01	8.485E+01	8.120E+01	1.118E-02	82.433%	83.188%	99.998%
7.505E+01	3.893E+01	3.590E+01	5.110E-04	91.939%	92.568%	100.000%
1.001E+02	1.981E+01	1.781E+01	6.032E-05	95.899%	96.313%	100.000%
1.500E+02	6.7560806	5.8810587	—	98.601%	98.782%	—
2.000E+02	2.3011219	1.9406588	—	99.524%	99.598%	—
2.502E+02	0.7819828	0.63897791	—	99.838%	99.868%	—
3.002E+02	0.2661985	0.21076467	—	99.945%	99.956%	—

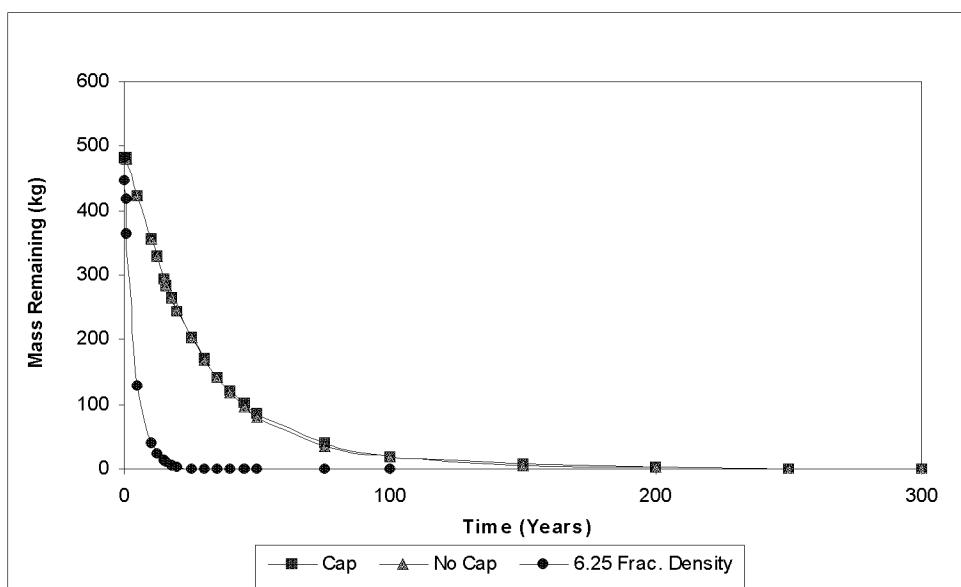


Figure A-22. Time release of methylene chloride from monolith, cap, no cap, and 6.25 fracture density.

Table A-23. Carbon tetrachloride.

Time Years	Mass Remaining			Mass Released		
	Cap	No Cap	Fracture	Cap	No Cap	Fracture
0.000E+000	1.70E+01	1.70E+01	1.70E+01	0	0	0
2.500E-01	1.70E+01	1.70E+01	1.58E+01	0.06%	0.06%	7.33%
5.000E-01	1.70E+01	1.70E+01	1.47E+01	0.22%	0.22%	13.61%
1.001E+000	1.69E+01	1.69E+01	1.28E+01	0.89%	0.89%	24.71%
5.003E+000	1.49E+01	1.49E+01	4.66E+00	12.15%	12.13%	72.62%
1.001E+01	1.25E+01	1.25E+01	1.52E+00	26.49%	26.42%	91.07%
1.201E+01	1.16E+01	1.16E+01	9.45E-01	31.75%	31.66%	94.45%
1.501E+01	1.04E+01	1.04E+01	4.95E-01	38.85%	38.75%	97.09%
1.601E+01	1.00E+01	1.00E+01	3.80E-01	41.13%	41.03%	97.77%
1.801E+01	9.30E+00	9.31E+00	2.37E-01	45.35%	45.27%	98.61%
2.001E+01	8.63E+00	8.64E+00	1.47E-01	49.27%	49.22%	99.13%
2.502E+01	7.20E+00	7.19E+00	5.13E-02	57.65%	57.74%	99.70%
3.002E+01	6.00E+00	5.96E+00	1.69E-02	64.71%	64.99%	99.90%
3.502E+01	5.04E+00	4.96E+00	6.74E-03	70.36%	70.82%	99.96%
4.003E+01	4.24E+00	4.13E+00	2.70E-03	75.10%	75.71%	99.98%
4.503E+01	3.56E+00	3.44E+00	1.08E-03	79.09%	79.79%	99.99%
5.003E+01	2.99E+00	2.86E+00	4.33E-04	82.43%	83.19%	100.00%
7.505E+01	1.37E+00	1.26E+00	1.98E-05	91.94%	92.57%	100.00%
1.001E+02	6.98E-01	6.27E-01	2.34E-06	95.90%	96.31%	100.00%
1.500E+02	2.38E-01	2.07E-01	—	98.60%	98.78%	—
2.000E+02	8.10E-02	6.83E-02	—	99.52%	99.60%	—
2.502E+02	2.75E-02	2.25E-02	—	99.84%	99.87%	—
3.002E+02	9.37E-03	7.42E-03	—	99.94%	99.96%	—

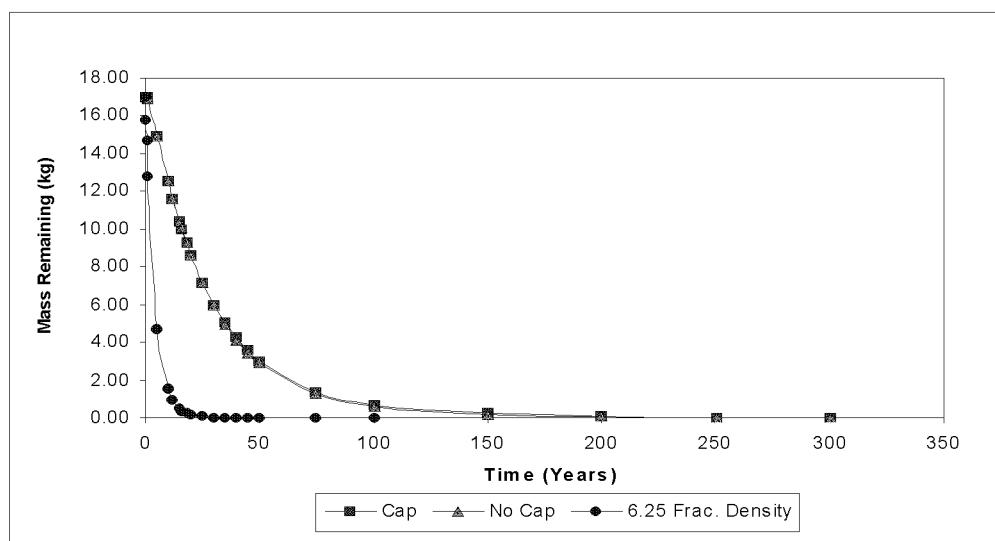


Figure A-23. Time of release of carbon tetrachloride from monolith, cap, no cap, and 6.25 fracture conditions.

Table A-24. Tetrachloroethylene.

Time	Mass Remaining			Mass Released		
	Years	Cap	No Cap	Fracture	Cap	No Cap
0.000E+00	3.048E+00	3.048E+00	3.05E+00	0.000%	0.000%	0.000%
2.500E-01	3.047E+00	3.047E+00	2.83E+00	0.056%	0.056%	7.333%
5.000E-01	3.042E+00	3.042E+00	2.63E+00	0.225%	0.225%	13.625%
1.001E+00	3.021E+00	3.021E+00	2.29E+00	0.890%	0.890%	24.823%
5.003E+00	2.678E+00	2.679E+00	8.16E-01	12.148%	12.133%	73.225%
1.001E+01	2.241E+00	2.243E+00	2.48E-01	26.486%	26.417%	91.872%
1.201E+01	2.080E+00	2.083E+00	1.54E-01	31.752%	31.665%	94.945%
1.501E+01	1.864E+00	1.867E+00	8.07E-02	38.850%	38.755%	97.353%
1.601E+01	1.795E+00	1.798E+00	6.19E-02	41.130%	41.034%	97.969%
1.801E+01	1.666E+00	1.668E+00	3.858E-02	45.356%	45.273%	98.735%
2.001E+01	1.546E+00	1.548E+00	2.405E-02	49.270%	49.216%	99.211%
2.502E+01	1.291E+00	1.288E+00	8.376E-03	57.654%	57.742%	99.725%
3.002E+01	1.076E+00	1.067E+00	2.749E-03	64.713%	64.987%	99.910%
3.502E+01	9.034E-01	8.895E-01	1.099E-03	70.363%	70.820%	99.964%
4.003E+01	7.589E-01	7.405E-01	4.400E-04	75.105%	75.707%	99.986%
4.503E+01	6.375E-01	6.161E-01	1.762E-04	79.088%	79.789%	99.994%
5.003E+01	5.355E-01	5.124E-01	7.060E-05	82.435%	83.190%	99.998%
7.505E+01	2.457E-01	2.265E-01	—	91.941%	92.569%	—
1.001E+02	1.250E-01	1.124E-01	—	95.899%	96.314%	—
1.500E+02	0.0426313	0.037111	—	98.602%	98.783%	—
2.000E+02	0.01452	0.01224585	—	99.524%	99.598%	—
2.502E+02	0.0049342	0.00403198	—	99.838%	99.868%	—
3.002E+02	0.0016797	0.00132991	—	99.945%	99.956%	—

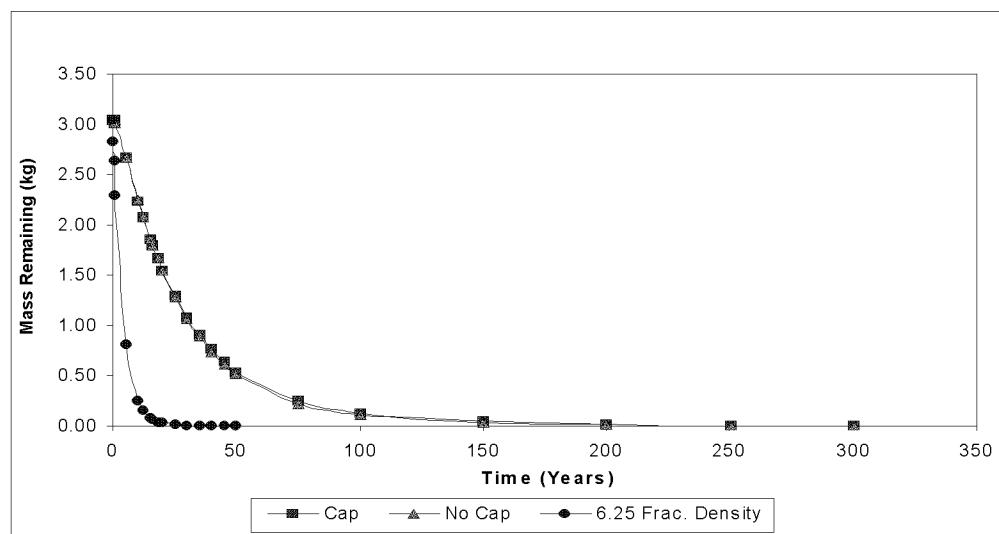


Figure A-24. Time of release of tetrachloroethylene from the monolith, cap, no cap, and 6.25 fracture conditions.

## **Appendix B**

### **Estimation of Thermal Stresses in a Grouted Waste Monolith Under Freezing Conditions**

**Brian D. Hawkes**



## Appendix B

# Estimation of Thermal Stresses in a Grouted Waste Monolith Under Freezing Conditions

Brian D. Hawkes

### Purpose

This analysis examines the thermal stresses caused by freezing in a block of grout that measures 125×125×10-ft thick, located at the Radioactive Waste Management Complex (RWMC).

### Scope

This analysis only deals with the calculated thermal stresses in the block of grout. No other analysis has been performed.

### Safety Category

No safety category is applicable for this analysis.

### Natural Phenomena Hazards Performance Category

This analysis has not been assigned to a performance category.

### Structure, System, or Component Description

This analysis examines the stresses in a block of grout, measuring 125×125×10-ft thick, and located at the RWMC. The bottom of this block will be buried 15-ft deep with the top of the block exposed to the atmosphere. Soil will surround the sides and bottom of the block (see Figure B-2).

### Materials

Several types of grout have been proposed for this block (Loomis et al. 2002). The properties vary widely depending on the components mixed with the grout and the type of grout. The grout material properties listed in Table B-1 were used in this analysis and are representative of all the grouts, not one particular type.

Table B-1. Typical grout properties.

Property	Value
Modulus of elasticity <sup>a</sup> ( $E = 57000\sqrt{f'_c}$ )	$2.068 \times 10^{10} \text{ Pa (3} \times 10^6 \text{ psi)}$
Density <sup>b</sup>	$1,860 \text{ Kg/m}^3 (116 \text{ lbf/ft}^3)$
Specific heat <sup>c</sup>	$780 \text{ J/Kg } ^\circ\text{C}$
Coefficient of thermal expansion <sup>d</sup>	$9.9 \times 10^{-6}/^\circ\text{C}$
Thermal conductivity <sup>c</sup>	$0.72 \text{ W/m } ^\circ\text{C}$
Poisson's ratio <sup>b</sup>	0.20

a. ACI 318-02, Section 8.5 – $f'_c$  is estimated to be 2,770 psi.

b. Estimated

c. J. P. Holman, *Heat Transfer*, McGraw-Hill, 1976.

d. Grout properties are listed in Loomis et al. (2002).

Table B-2. Soil properties.<sup>a</sup>

Property	Value
Modulus of elasticity	$6.89 \times 10^7$ Pa (10 ksi)
Density	2,180 Kg/m <sup>3</sup> (136 lbf/ft <sup>3</sup> )
Specific heat	1,300 J/Kg °C
Coefficient of thermal expansion	$9.9 \times 10^{-6}$ /°C
Thermal conductivity	0.2 W/m °C
Poisson's ratio	0.20

a. Soil properties are estimated using values from Bowles (1977) and Holman (1976).

## Loads

This analysis investigates the thermal stresses in the grout caused by freezing temperatures. The top surface of the grout block is 5 ft below the ground surface and left exposed to the atmosphere. For this analysis, the initial temperature of the soil and the grout block are 70°F (21.1°C) and the air temperature is 0°F (-17.77°C). This cold temperature is maintained for 10 days. The calculated heat transfer coefficient between the air and the grout and the air and the soil is 7.1 W/m<sup>2</sup> °C (see Appendix A).

A second finite element model, using the same node and element numbers, used this temperature distribution to calculate thermal stresses. This model used stress elements and the boundary restraints shown in Figure B-1. Contact surfaces were used between the soil and the grout to allow the block to move independently of the soil.

Freezing effects of the soil were not considered in this analysis.

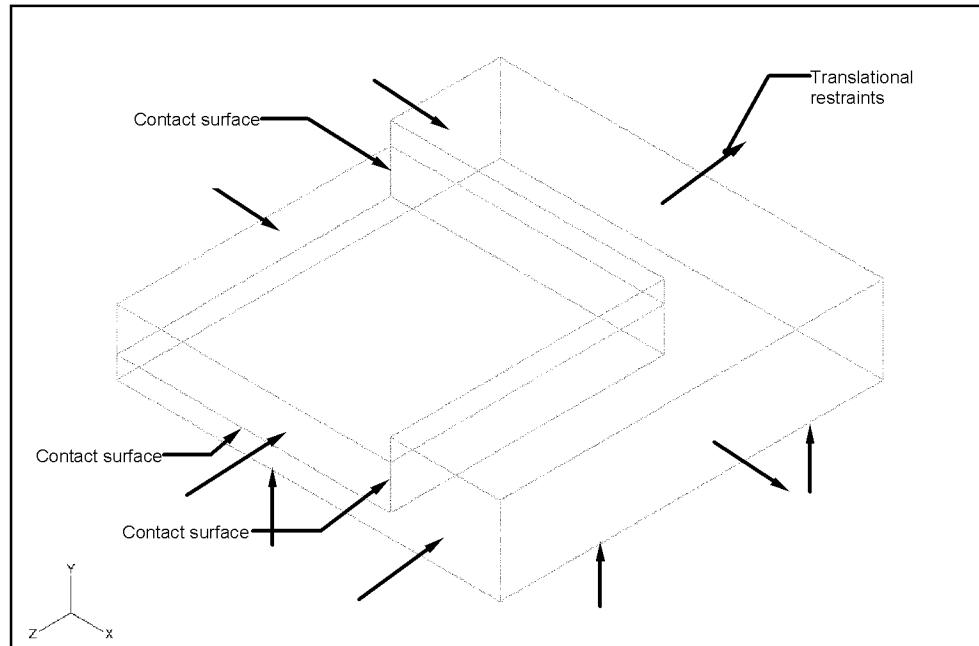


Figure B-1. Boundary conditions for the stress model. The nodes on the surfaces were restrained from translating in the directions shown.

## Assumptions

The following assumptions are made for this analysis:

1. The soil and grout are in perfect thermal contact. There is no impedance in the heat transfer between the soil and the grout because of a gap.
2. The heat transfer coefficient is constant over the entire exposed surface of the grout and the soil.
3. An initial temperature of 70°F for the soil and the grout, followed by 10 days of 0°F air temperature, would produce a large, but reasonable temperature difference within the grout block to produce the thermal strain.
4. The thermal expansion coefficient for the soil is the same as for the grout.

## Calculations

An ABAQUS (Hibbit, Karlsson & Sorenson 2002) finite element model of the grout and soil was created for this analysis. Only one quarter of the model was used, which reduced the size of the model and the solution time (see Figure B-2). The soil in the finite element model was extended 25 ft (7.62 m) beyond the grout block to the east (+X) and to the north (+Z). The soil extends 5 ft below (-Y) the grout pad as well. Temperature of the grout and soil initially was assigned at 70°F (21.1°C). A heat transfer coefficient of 7.1 W/m<sup>2</sup>°C was assigned to all the element faces exposed to the air. The air was assumed to be at 0°F (-17.77°C) for 10 days. This lower temperature cooled the grout block and the soil and induced thermal strain and stress in the grout block (see Figure B-3).

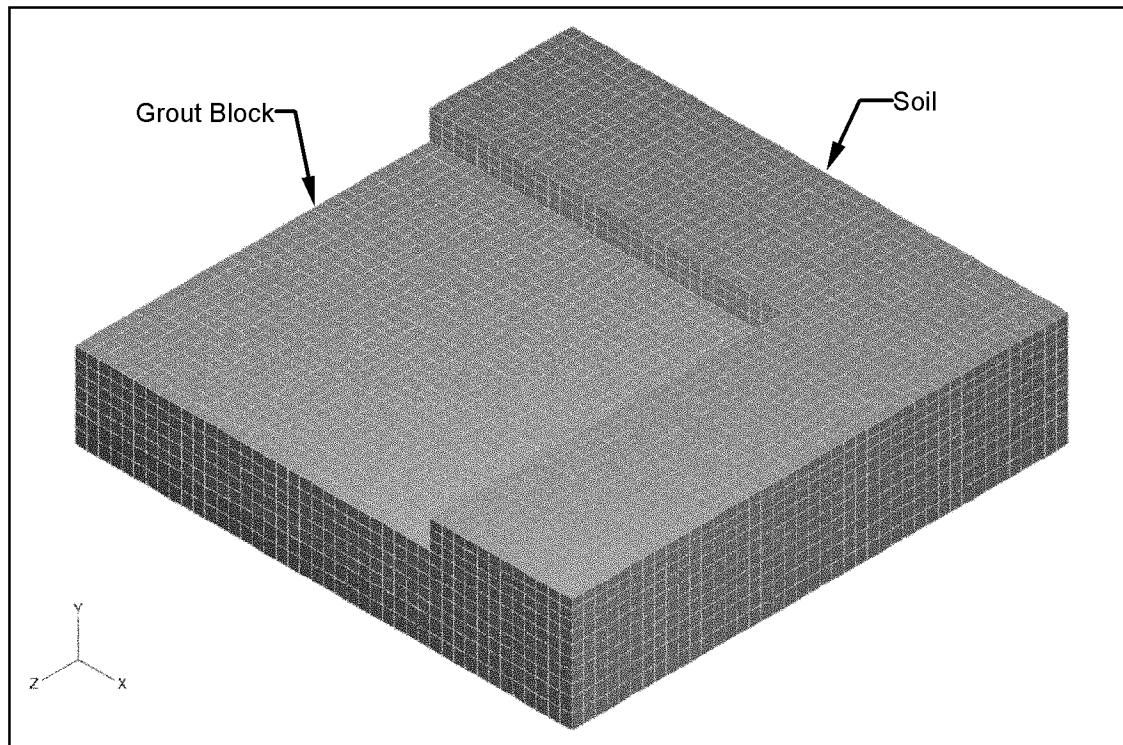


Figure B-2. Quarter model of the grout block and soil.

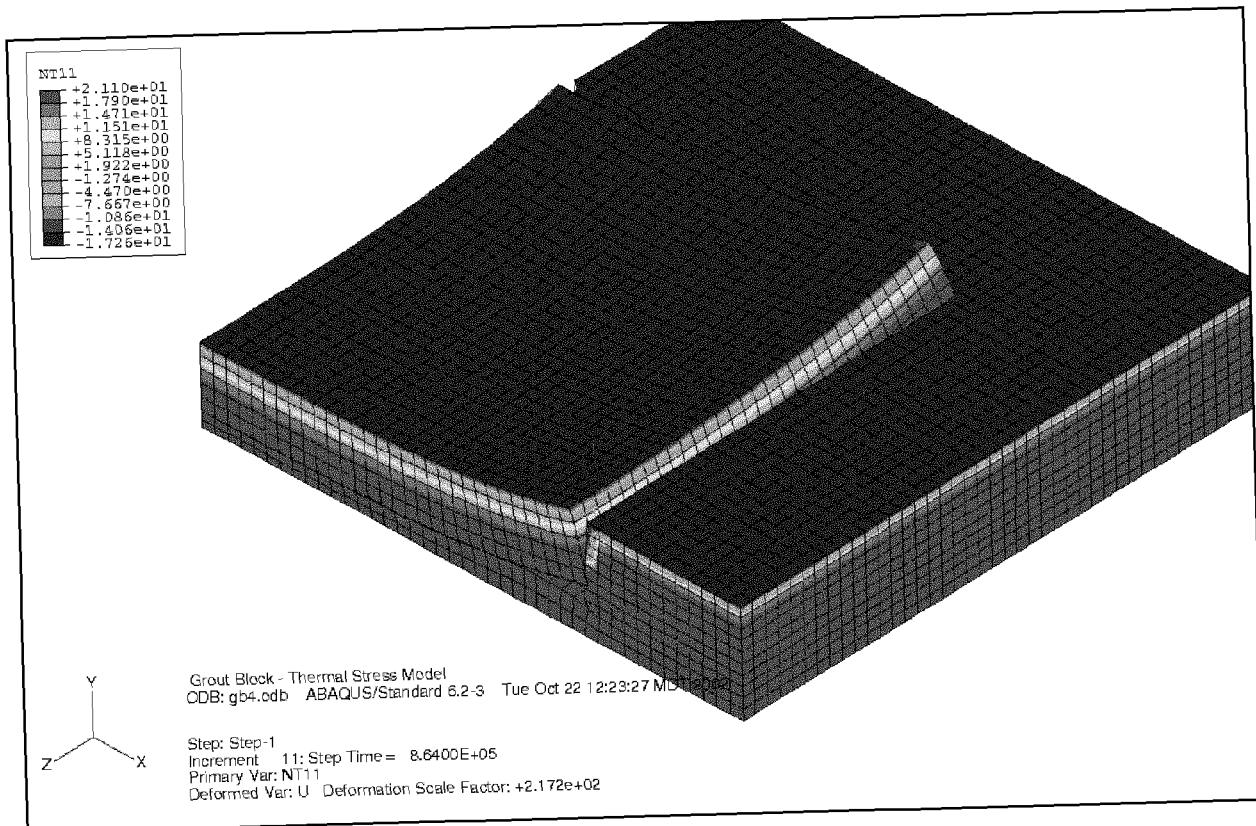


Figure B-3. Temperature distribution after 10 days of 0°F temperatures.

A second finite element model of the grout and soil was created to calculate the thermal stresses using the temperatures calculated by the first model (see Figure B-4). This model used contact surfaces between the soil and the grout so the grout could move independently of the soil.

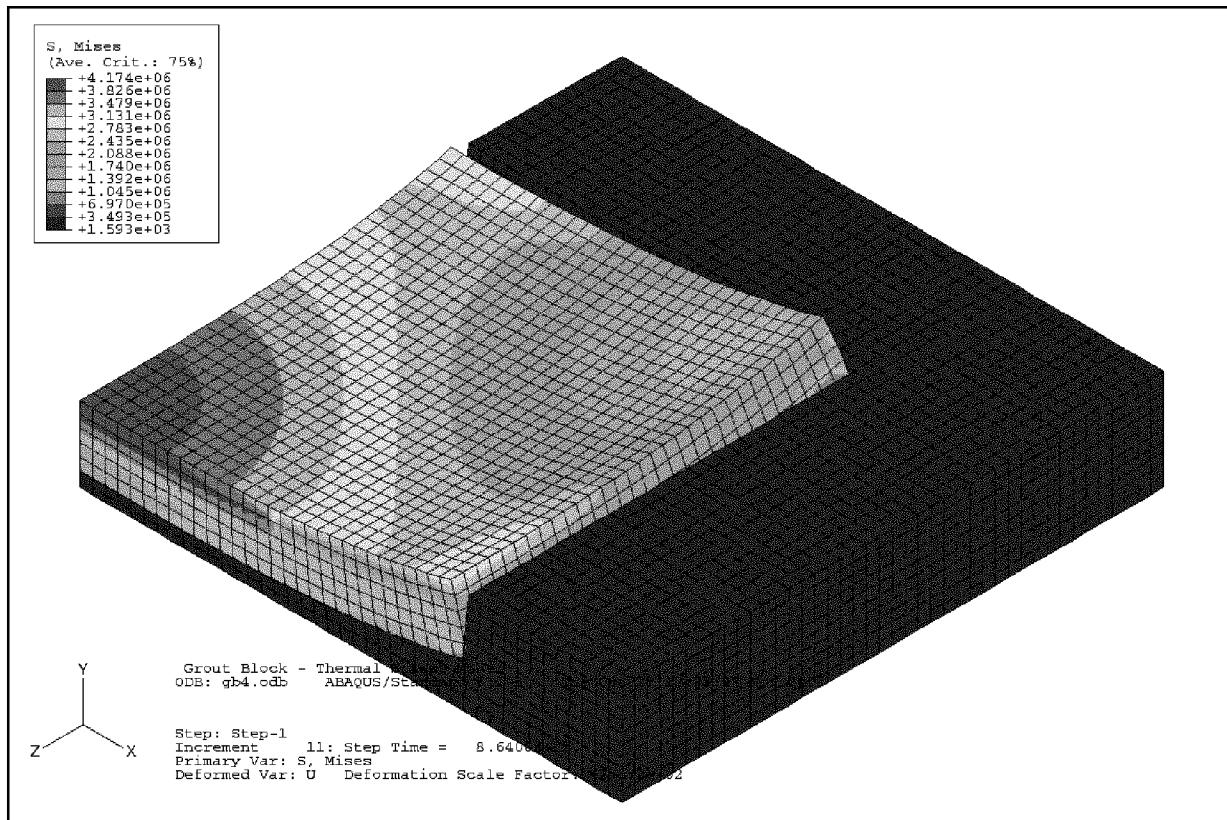


Figure B-4. Von Mises stresses caused by thermal contraction in the grout block.

Results of this model using the estimated grout and soil properties are shown in Figure B-4. Cracks will occur when the maximum principal stress exceeds the tensile splitting strength of the grout.

Some additional runs were made using modified grout and soil properties. Results of these runs are listed in Table B-3 and are shown in Figures B-5 through B-8. Table B-4 shows tensile strength values from the Final Results Report In Situ Grouting Technology for Application in Buried Transuranic Waste Sites, Volume 1, Technology Description and Treatability Study Results for Operable Unit 7-13/14 (Loomis et al. 2002).

Results of each of these ABAQUS runs are shown with Von Mises stresses. These stresses are a good indicator of the magnitude and location of the highest tensile stresses, because cracks in the grout are caused by tensile stresses.

Table B-3. Results from modified material properties.

Description	Typical Value	Modified Value	Maximum Von Mises Stress
Typical grout and soil material properties			4.174e6 Pa (605 psi)
Increased modulus of elasticity for grout	2.068e10 Pa	2.76e10 Pa	5.137e6 Pa (745 psi)
Decreased modulus of elasticity for grout	2.068e10 Pa	6.89e9 Pa	1.629e6 Pa (236 psi)
Increased modulus of elasticity for soil	6.89e7 Pa	13.8e7 Pa	4.428e6 Pa (642 psi)
Increased coefficient of thermal expansion for grout	9.9e-6 /°C	13.0e-6 /°C	5.224e6 Pa (758 psi)

Table B-4. Grout tensile strengths (MPa) (sample average).

Grout Description	Modified Tank Closure (C75)	Enviroblend (E)	Salt Stone (S)	Test HG (T)	US Grout (U)
Neat	4.87	0.09	0.92	5.15	3.50
12% Nitrate salts	2.35	0.03	0.60	2.03	1.58
9% Organic sludge	3.46	0.12	0.68	2.14	1.21
50% INEEL soil	2.44	0.02	0.92	2.13	1.53
Average	3.28	0.07	0.78	2.86	1.96

INEEL = Idaho National Engineering and Environmental Laboratory

Table B-5. Grout compressive strengths (MPa) (sample average).

Grout Description	Modified Tank Closure (C75)	Enviroblend (E)	Salt Stone (S)	Test HG (T)	US Grout (U)
Neat	48.68	0.68	9.54	50.60	60.81
12% Nitrate salts	34.36	0.19	4.40	16.43	27.52
9% Organic sludge	37.24	0.80	7.02	13.66	20.85
50% INEEL soil	18.18	0.24	7.38	13.63	17.48
Average	34.62	0.48	7.09	23.58	31.67
Modulus of elasticity <sup>1</sup>	2.78e10 Pa	3.28e9 Pa	1.26e10 Pa	2.30e10 Pa	2.66e10 Pa

INEEL = Idaho National Engineering and Environmental Laboratory

1. Based on  $E = 57000 * \sqrt{f_c'}$  using English units

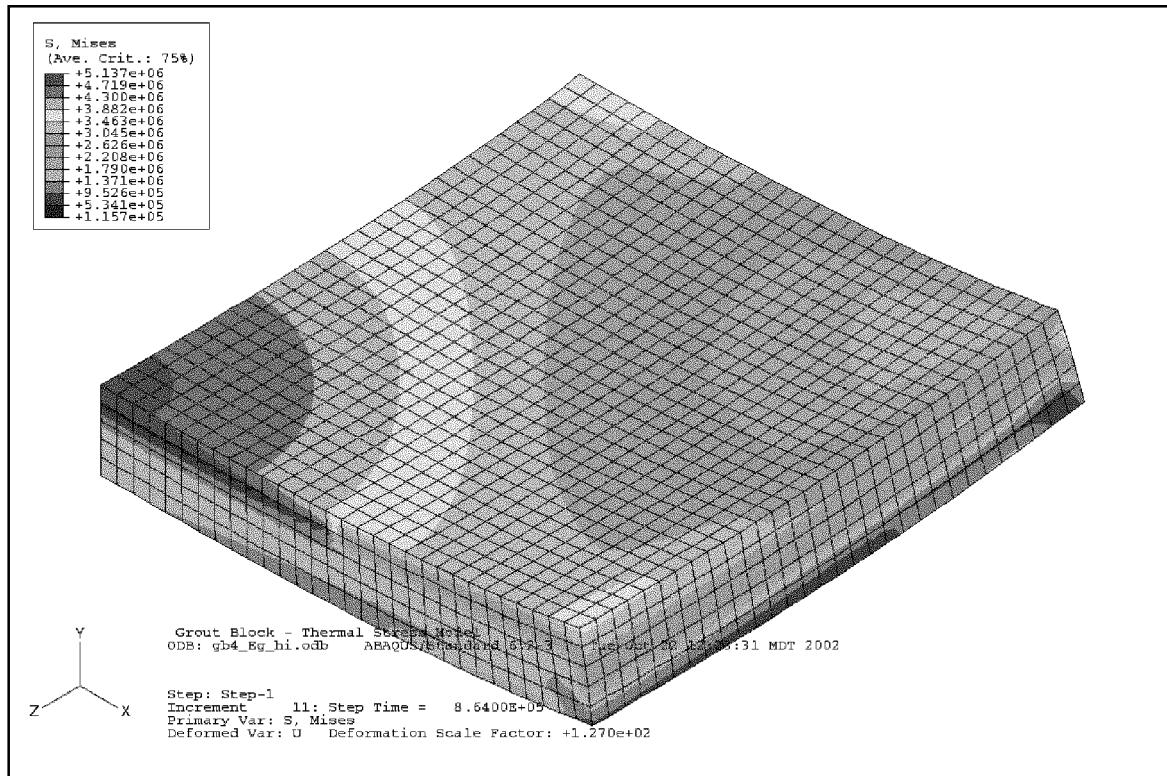


Figure B-5. Results from increasing the modulus of elasticity of the grout.

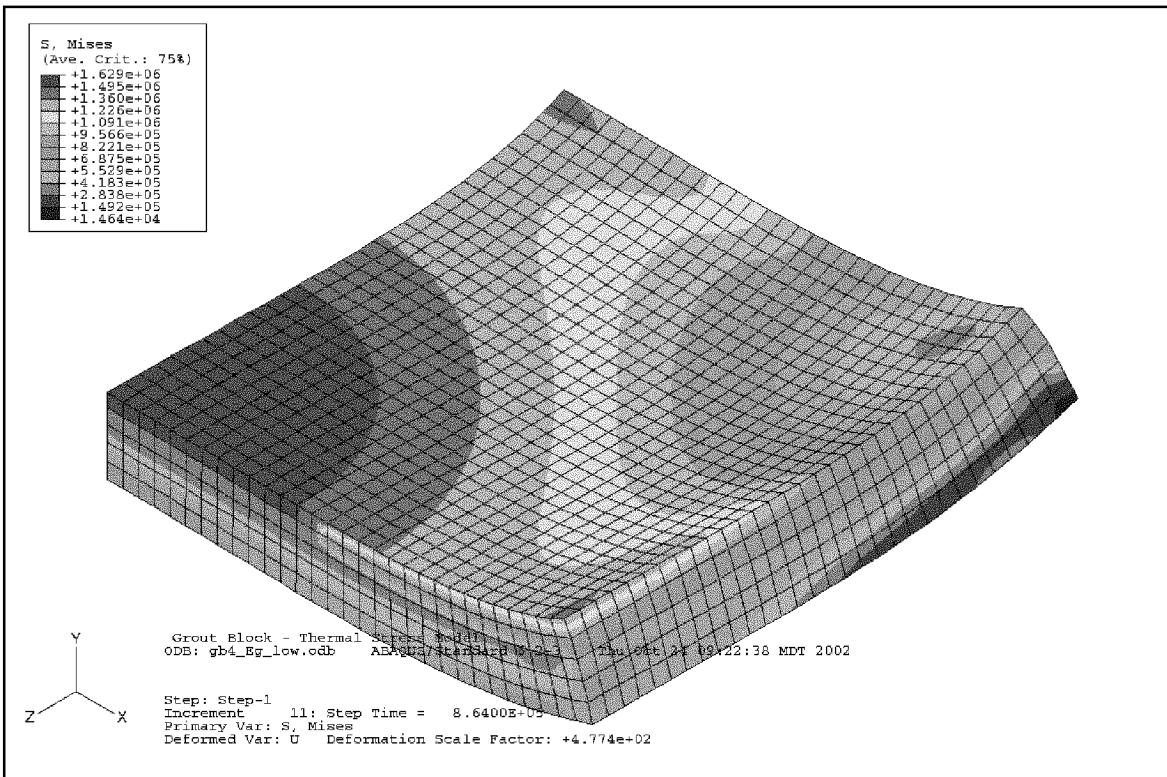


Figure B-6. Results from lowering the elastic modulus of the grout.

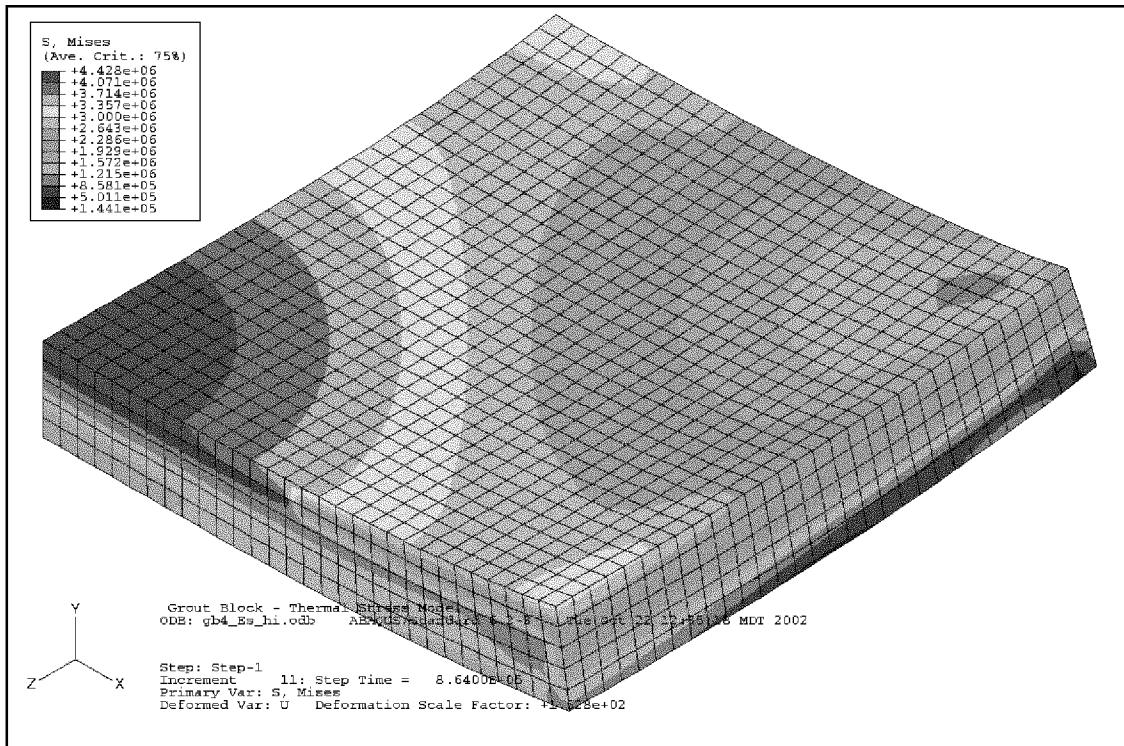


Figure B-7. Results from increasing the elastic modulus of the soil.

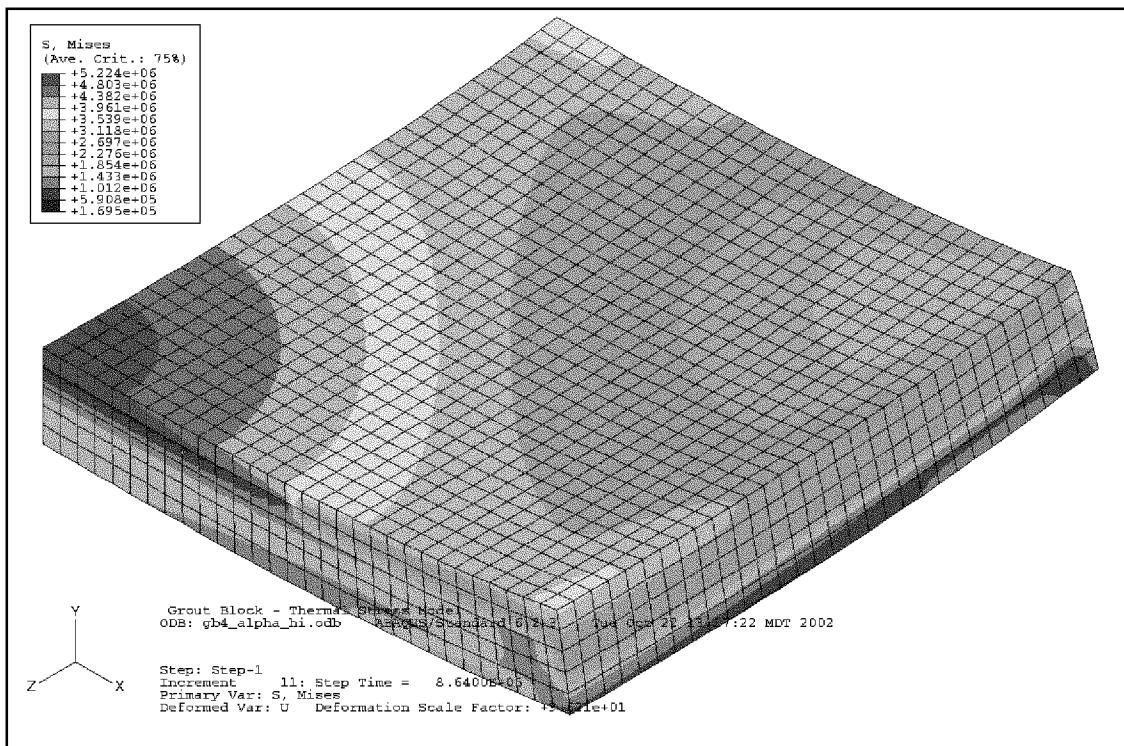


Figure B-8. Results from increasing the coefficient of thermal expansion for the grout.

## **Conclusions**

This analysis shows the results of the first iteration of finding thermal stresses caused by cold temperatures on the grout block. The temperature differences calculated will cause enough thermal strain to cause cracking in the grout block for each of the grouts listed. This analysis shows that the stronger grouts (higher modulus of elasticity) have higher thermal stresses. The lower strength grouts have lower thermal stresses.

## **Recommendations**

It is recommended that this analysis be re-run using historical temperatures, which will result in higher temperatures (lower temperature differences) and less stress. Also, it is necessary to obtain the coefficient of thermal expansion and modulus of elasticity for each grout because the range in values for these properties varies widely and directly affects the results.

## **References**

- Bowles, J. E., 1977, *Foundation Analysis and Design*, McGraw-Hill Book Company, 2<sup>nd</sup> Edition.
- Hibbitt, Karlsson & Sorenson, Inc., 2002, ABAQUS/Standard Version 6.3, Pawtucket, Rhode Island.
- Holman, J. P., 1976, *Heat Transfer*, McGraw-Hill, Inc., 4<sup>th</sup> Edition.
- Loomis, G. G., C. M. Miller, A. L. Sehn, J. J. Jessmore, and J. R. Weidner, 2002, *Final Results Report In Situ Grouting Technology for Application in Buried Transuranic Waste Sites, Volume 1, Technology Description and Treatability Study Results for Operable Unit 7-13/14*, INEEL/EXT-02-00233, Rev. 0, Idaho National Engineering and Environmental Laboratory.

# ABAQUS INPUT FILES

## ABBREVIATED ABAQUS INPUT FILES

### Thermal Model

```
** file = gb3.inp
** final mesh for heat transfer problem. Element length ~2ft
*** =====
***%
***%           I-DEAS 9 ABAQUS STANDARD TRANSLATOR
***%           FOR ABAQUS VERSION 5.8
***%
***%           MODEL FILE: E:\bdh\ms9\Grout_block_final_mesh.mf1
***%           INPUT FILE: gb3.inp
***%           EXPORTED: AT 14:24:14 ON 16-Oct-02
***%           PART: Assy_grout_soil
***%           FEM: HT_mesh
***%
***%           UNITS: SI-Meter (newton)
***%               ... LENGTH : meter
***%               ... TIME   : sec
***%               ... MASS    : kilogram (kg)
***%               ... FORCE   : newton(N)
***%               ... TEMPERATURE : deg Celsius
***%
***%           COORDINATE SYSTEM: PART
***%
***%           SUBSET EXPORT: OFF
***%
***%           NODE ZERO TOLERANCE: ON ( 0.1000E-06)
***%
***% =====
***%
***%
*HEADING
Grout Block - Heat Transfer Model
*NODE, NSET=ALLNODES, SYSTEM=R
    1, 1.9050000E+01,-4.5720000E+00,-1.9050000E+01
.....
    23138, 2.6035000E+01,-5.3340000E+00,-1.9685000E+01
*ELEMENT, TYPE=DC3D8 , ELSET=SOIL_EL
    10000, 10000, 10001, 10032, 10031, 10527, 10528, 10648, 10776
.....
    20439, 23138, 22887, 21397, 21395, 23049, 22899, 21398, 21396
*ELEMENT, TYPE=DC3D8 , ELSET=GROUT_EL
    1,     1,     2,     33,     32,    1021,    1020,     962,     1265
.....
    4500, 5766, 1293, 1298, 990, 2460, 1294, 1299, 1151
*SOLID SECTION,
ELSET=SOIL_EL,
MATERIAL=SOIL
*SOLID SECTION,
ELSET=GROUT_EL,
MATERIAL=GROUT
*****
** Define grout material properties
*****
*MATERIAL,NAME=GROUT
*conductivity
0.72
*density
```

```

1860.0
*specific heat
780.0
*****
** Define soil material properties
*****
*MATERIAL,NAME=SOIL
*conductivity
0.2
*density
2180
*specific heat
1300
*****
** define element groups
*****
*ELSET,ELSET=GROUT_EAST_EL
1,      31,      61,      91,      121,      151,      181,      211,      241,
271,      301
.....
4291,      4321,      4351,      4381,      4411,      4441,      4471
*ELSET,ELSET=GROUT_WEST_EL
30,      60,      90,      120,      150,      180,      210,      240,      270,
300,      330
.....
4320,      4350,      4380,      4410,      4440,      4470,      4500
*ELSET,ELSET=GROUT_BOT_EL
1,      2,      3,      4,      5,      6,      7,      8,      9,
10,      11
.....
892,      893,      894,      895,      896,      897,      898,      899,      900
*ELSET,ELSET=GROUT_TOP_EL
3601,      3602,      3603,      3604,      3605,      3606,      3607,      3608,      3609,
3610,      3611
.....
4492,      4493,      4494,      4495,      4496,      4497,      4498,      4499,      4500
*ELSET,ELSET=GROUT_NORTH_EL
1,      2,      3,      4,      5,      6,      7,      8,      9,
10,      11
.....
3624,      3625,      3626,      3627,      3628,      3629,      3630
*ELSET,ELSET=GROUT_SOUTH_EL
871,      872,      873,      874,      875,      876,      877,      878,      879,
880,      881
.....
4494,      4495,      4496,      4497,      4498,      4499,      4500
*ELSET,ELSET=SOIL_EAST_EL
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13021,      13022
.....
20427,      20439
*ELSET,ELSET=SOIL_WEST_EL
10029,      10059,      10089,      10119,      10149,      10179,      10209,      10239,      10269,
10299,      10329
.....
20148,      20149,      20150,      20151
*ELSET,ELSET=SOIL_BOT_EL
17812,      17813,      17814,      17815,      17816,      17817,      17818,      17819,      17820,
17821,      17822
.....
20436,      20437,      20438,      20439
*ELSET,ELSET=SOIL_TOP_EL

```

```

    11800,    11801,    11802,    11803,    11804,    11805,    11806,    11807,    11808,
11809,    11810
    .....
    16186,    16187,    16188,    16189,    16190,    16191
*ELSET,ELSET=SOIL_SOUTH_EL
    14061,    14091,    14121,    14151,    14181,    14211,    14241,    14271,    14301,
14331,    14361
    .....
    19428,    19429,    19430,    19431
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10009,    10010
    .....
    20306,    20307
*ELSET,ELSET=SOIL_BED_TOP_EL
    16912,    16913,    16914,    16915,    16916,    16917,    16918,    16919,    16920,
16921,    16922
    .....
    17803,    17804,    17805,    17806,    17807,    17808,    17809,    17810,    17811
*ELSET,ELSET=SOIL_BED_EAST_EL
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14041,    14042
    .....
    15495,    15496,    15497,    15498,    15499,    15500,    15501
*ELSET,ELSET=SOIL_BED_NORTH_EL
    10330,    10331,    10332,    10333,    10334,    10335,    10336,    10337,    10338,
10339,    10340
    .....
    11793,    11794,    11795,    11796,    11797,    11798,    11799
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    11811,    11823,    11835,    11847,    11859,    11871,    11883,    11895,    11907,
11919,    11931
    .....
    12867,    12879
*ELSET,ELSET=SOIL_EAST_SIDE_EL
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15841,    15842
    .....
    16580,    16581
*ELSET,ELSET=SOIL_TOP_EAST_EL
    15832,    15833,    15834,    15835,    15836,    15837,    15838,    15839,    15840,
15841,    15842
    .....
    16184,    16185,    16186,    16187,    16188,    16189,    16190,    16191
*ELSET,ELSET=SOIL_TOP_NORTH_EL
    11800,    11801,    11802,    11803,    11804,    11805,    11806,    11807,    11808,
11809,    11810
    .....
    12152,    12153,    12154,    12155,    12156,    12157,    12158,    12159
*ELSET,ELSET=SOIL_TOP_NE_EL
    13600,    13601,    13602,    13603,    13604,    13605,    13606,    13607,    13608,
13609,    13610
    .....
    13743,
*****
** Define initial conditions (temperature = 70 deg F)
*****
*initial conditions, type=temperature
allnodes, 21.1
*****
** Define surfaces
*****
*surface, name=grout_top, type=element

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grout_top_el, s2
*surface, name=grout_east, type=element
grout_east_el, s6
*surface, name=grout_bot, type=element
grout_bot_el, s1
*surface, name=grout_north, type=element
grout_north_el, s3
*surface, name=soil_bed_top, type=element
soil_bed_top_el, s1
*surface, name=soil_bed_east, type=element
soil_bed_east_el, s3
*surface, name=soil_bed_north, type=element
soil_bed_north_el, s5
*surface, name=soil_north_side, type=element
soil_north_side_el, s4
*surface, name=soil_east_side, type=element
soil_east_side_el, s3
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** Define contact pairs
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*contact pair, interaction=int1
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*contact pair, interaction=int1
soil_bed_north, grout_north
*contact pair, interaction=int1
soil_bed_east, grout_east
*surface interaction, name=int1
*gap conductance
0.72, 0.0, 1.66
0.72, 1.0, 1.66
*STEP, INC=150
*HEAT TRANSFER
14400.0, 864000.0, ,
*film
soil_top_north_el, f1, -17.77, 7.1
*film
soil_top_east_el, f1, -17.77, 7.1
*film
soil_top_ne_el, f1, -17.77, 7.1
*film
soil_east_side_el, f3, -17.77, 7.1
*film
soil_north_side_el, f4, -17.77, 7.1
*film
grout_top_el, f2, -17.77, 7.1
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*node file, nset=allnodes
nt
*END STEP

```

### Stress Model

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** final mesh for thermal stress problem. Element length ~2ft
***% =====
***%
***%          I-DEAS 9 ABAQUS STANDARD TRANSLATOR
***%          FOR ABAQUS VERSION 5.8
***%
***%          MODEL FILE: E:\bdh\ms9\Grout_block_final_mesh.mf1

```

```

*** INPUT FILE: gb4.inp
*** EXPORTED: AT 14:24:14 ON 16-Oct-02
*** PART: Assy_grout_soil
*** FEM: HT_mesh
*** UNITS: SI-Meter (newton)
***     ... LENGTH : meter
***     ... TIME   : sec
***     ... MASS    : kilogram (kg)
***     ... FORCE   : newton(N)
***     ... TEMPERATURE : deg Celsius
*** COORDINATE SYSTEM: PART
*** SUBSET EXPORT: OFF
*** NODE ZERO TOLERANCE: ON ( 0.1000E-06)
*** =====
*** *HEADING
Grout Block - Thermal Stress Model
*NODE, NSET=ALLNODES, SYSTEM=R
    1, 1.9050000E+01,-4.5720000E+00,-1.9050000E+01
.....
    23138, 2.6035000E+01,-5.3340000E+00,-1.9685000E+01
*ELEMENT, TYPE=C3D8 , ELSET=SOIL_EL
    10000, 10000, 10001, 10032, 10031, 10527, 10528, 10648, 10776
.....
    20439, 23138, 22887, 21397, 21395, 23049, 22899, 21398, 21396
*ELEMENT, TYPE=C3D8 , ELSET=GROUT_EL
    1, 1, 2, 33, 32, 1021, 1020, 962, 1265
.....
    4500, 5766, 1293, 1298, 990, 2460, 1294, 1299, 1151
*SOLID SECTION,
ELSET=SOIL_EL,
MATERIAL=SOIL
*SOLID SECTION,
ELSET=GROUT_EL,
MATERIAL=GROUT
***** 
** Define grout material properties
*****
*MATERIAL,NAME=GROUT
*ELASTIC,TYPE=ISOTROPIC
**
** E = 57000*fc^.5
** for 6000 psi grout, E=4.4e6 psi or 3.034e10 pascals
** 6000 psi is too high. A value of 2770 psi fits in the average for this
** grout.
**
    2.068E+10, 0.20
**
** coef. of thermal expansion varies from 5.5e-6 in/in/deg F (9.9e-6 /deg C)
** for concrete
** to 30e-6 /deg F (54e-6 /deg C) for epoxy grouts
*expansion
    9.9E-06
*conductivity
    0.72
*density
    1860.0

```

```

*specific heat
780.0
*****
** Define soil material properties
*****
*MATERIAL,NAME=SOIL
*ELASTIC,TYPE=ISOTROPIC
**
** Bowles uses 10 - 20 ksi for E for sand and gravel (6.89E7 to 1.379E8 pascals)
**
** 6.89E+07, 0.20
6.89E+07, 0.20
**
** coefficient of thermal expansion is the same as the grout
**
*expansion
9.9E-06
*conductivity
0.2
*density
2180
*specific heat
1300
*****
** define element groups
*****
*ELSET,ELSET=GROUT_EAST_EL
1,      31,      61,      91,      121,      151,      181,      211,      241,
271,     301
.....
4291,    4321,    4351,    4381,    4411,    4441,    4471
*ELSET,ELSET=GROUT_WEST_EL
30,      60,      90,      120,      150,      180,      210,      240,      270,
300,     330
.....
4320,    4350,    4380,    4410,    4440,    4470,    4500
*ELSET,ELSET=GROUT_BOT_EL
1,       2,       3,       4,       5,       6,       7,       8,       9,
10,      11
.....
892,     893,     894,     895,     896,     897,     898,     899,     900
*ELSET,ELSET=GROUT_TOP_EL
3601,    3602,    3603,    3604,    3605,    3606,    3607,    3608,    3609,
3610,    3611
.....
4492,    4493,    4494,    4495,    4496,    4497,    4498,    4499,    4500
*ELSET,ELSET=GROUT_NORTH_EL
1,       2,       3,       4,       5,       6,       7,       8,       9,
10,      11
.....
3624,    3625,    3626,    3627,    3628,    3629,    3630
*ELSET,ELSET=GROUT_SOUTH_EL
871,     872,     873,     874,     875,     876,     877,     878,     879,
880,     881
.....
4494,    4495,    4496,    4497,    4498,    4499,    4500
*ELSET,ELSET=SOIL_EAST_EL
13012,   13013,   13014,   13015,   13016,   13017,   13018,   13019,   13020,
13021,   13022
.....
20427,   20439
*ELSET,ELSET=SOIL_WEST_EL

```

```

    10029,    10059,    10089,    10119,    10149,    10179,    10209,    10239,    10269,
10299,    10329
    .....
    20148,    20149,    20150,    20151
*ELSET,ELSET=SOIL_BOT_EL
    17812,    17813,    17814,    17815,    17816,    17817,    17818,    17819,    17820,
17821,    17822
    .....
    20436,    20437,    20438,    20439
*ELSET,ELSET=SOIL_TOP_EL
    11800,    11801,    11802,    11803,    11804,    11805,    11806,    11807,    11808,
11809,    11810
    .....
    16186,    16187,    16188,    16189,    16190,    16191
*ELSET,ELSET=SOIL_SOUTH_EL
    14061,    14091,    14121,    14151,    14181,    14211,    14241,    14271,    14301,
14331,    14361
    .....
    19428,    19429,    19430,    19431
*ELSET,ELSET=SOIL_NORTH_EL
    10000,    10001,    10002,    10003,    10004,    10005,    10006,    10007,    10008,
10009,    10010
    .....
    20306,    20307
*ELSET,ELSET=SOIL_BED_TOP_EL
    16912,    16913,    16914,    16915,    16916,    16917,    16918,    16919,    16920,
16921,    16922
    .....
    17803,    17804,    17805,    17806,    17807,    17808,    17809,    17810,    17811
*ELSET,ELSET=SOIL_BED_EAST_EL
    14032,    14033,    14034,    14035,    14036,    14037,    14038,    14039,    14040,
14041,    14042
    .....
    15495,    15496,    15497,    15498,    15499,    15500,    15501
*ELSET,ELSET=SOIL_BED_NORTH_EL
    10330,    10331,    10332,    10333,    10334,    10335,    10336,    10337,    10338,
10339,    10340
    .....
    11793,    11794,    11795,    11796,    11797,    11798,    11799
*ELSET,ELSET=SOIL_NORTH_SIDE_EL
    11811,    11823,    11835,    11847,    11859,    11871,    11883,    11895,    11907,
11919,    11931
    .....
    12867,    12879
*ELSET,ELSET=SOIL_EAST_SIDE_EL
    15832,    15833,    15834,    15835,    15836,    15837,    15838,    15839,    15840,
15841,    15842
    .....
    16580,    16581
*ELSET,ELSET=SOIL_TOP_EAST_EL
    15832,    15833,    15834,    15835,    15836,    15837,    15838,    15839,    15840,
15841,    15842
    .....
    16184,    16185,    16186,    16187,    16188,    16189,    16190,    16191
*ELSET,ELSET=SOIL_TOP_NORTH_EL
    11800,    11801,    11802,    11803,    11804,    11805,    11806,    11807,    11808,
11809,    11810
    .....
    12152,    12153,    12154,    12155,    12156,    12157,    12158,    12159
*ELSET,ELSET=SOIL_TOP_NE_EL
    13600,    13601,    13602,    13603,    13604,    13605,    13606,    13607,    13608,
13609,    13610
    .....

```

```

13743,
*NSET,NSET=BS000001
31,62,93,124,155,186,217,248,279,310,341,372,403,434,465,496
.....
22888,22889,22890,22891,22892,22893,22894,22895,22896,22897
*NSET,NSET=BS000002
18542,18545,18548,18551,18552,18554,18557,18560,18561,18563,18566,18569
.....
23049,
*NSET,NSET=BS000003
19623,19624,19625,19626,19627,19628,19629,19630,19631,19632,19633,19634
.....
22900,22901,22902,22903,22904,22905,22906,22907,22908,22909
*NSET,NSET=BS000004
931,932,933,934,935,936,937,938,939,940,941,942,943,944,945,946
.....
22863,22864,22865,22866,22867,22868,22869,22870,22871,22872,22873
*NSET,NSET=BS000005
961,1295,1296,1297,1298,1299,10030,10433,10464,10495,10526,10557,12808
.....
22862,
*NSET,NSET=BS000006
19531,19564,19565,19566,19567,19568,19569,19570,19571,19572,19573,19574
.....
22877,22878,22879,22880,22881,22882,22883,22884,22885,22886
*NSET,NSET=BS000007
19563,21447,22155,22875
*****
** Define initial conditions (temperature = 70 deg F)
*****
*initial conditions, type=temperature
allnodes, 21.1
*****
** Define surfaces
*****
*surface, name=grout_top, type=element
grout_top_el, s2
*surface, name=grout_east, type=element
grout_east_el, s6
*surface, name=grout_bot, type=element
grout_bot_el, s1
*surface, name=grout_north, type=element
grout_north_el, s3
*surface, name=soil_bed_top, type=element
soil_bed_top_el, s1
*surface, name=soil_bed_east, type=element
soil_bed_east_el, s3
*surface, name=soil_bed_north, type=element
soil_bed_north_el, s5
*surface, name=soil_north_side, type=element
soil_north_side_el, s4
*surface, name=soil_east_side, type=element
soil_east_side_el, s3
*****
** Define contact pairs
*****
*contact pair, interaction=int1
soil_bed_top, grout_bot
*contact pair, interaction=int1
soil_bed_north, grout_north
*contact pair, interaction=int1
soil_bed_east, grout_east
*surface interaction, name=int1

```

```
*friction
 0.4
*STEP, INC=150
*static
14400.0, 864000.0,,
*dload
 grout_el, grav, -9.8, 0.0, 1.0, 0.0
*dload
 soil_el, grav, -9.8, 0.0, 1.0, 0.0
*BOUNDARY, OP=NEW
BS000001,    1,,      0.00000E+00
BS000002,    2,,      0.00000E+00
BS000003,    1, 2,    0.00000E+00
BS000004,    3,,      0.00000E+00
BS000005,    1,,      0.00000E+00
BS000006,    3,,      0.00000E+00
BS000007,    2, 3,    0.00000E+00
BS000007,    1, 3,    0.00000E+00
*monitor, dof=2, node=1299
*TEMPERATURE, FILE=gb3
*OUTPUT, FIELD, VAR=PRESELECT
*NODE OUTPUT, NSET=ALLNODES
 NT
*END STEP
```

## **Appendix C**

### **Estimation of Seismic Stresses in a Grouted Waste Monolith at the Radioactive Waste Management Complex**

**Brian D. Hawkes**



## Appendix C

# Estimation of Seismic Stresses in a Grouted Waste Monolith at the Radioactive Waste Management Complex

Brian D. Hawkes

### Purpose

This analysis examines seismic stresses at the Radioactive Waste Management Complex (RWMC) in a block of grout that measures 125- $\times$  125-  $\times$  10-ft thick for 1,000-year, 10,000-year, and 100,000-year earthquakes.

### Scope

This analysis only deals with the block of grout and its estimated seismic response. No other analysis has been performed.

### Safety Category

No safety category is applicable for this analysis.

### Natural Phenomena Hazards Performance Category

This analysis has not been assigned to a performance category.

### Structure, System, or Component Description

This analysis examines the stresses in a block of grout that measures 125- $\times$ 125- $\times$ 10-ft thick located at RWMC. The bedrock in this area is approximately 20 ft below ground level. Two cases were investigated: (1) the block sits on bedrock covered by 10 ft of soil and (2) the block sits on 5 ft of soil and is covered by 5 ft of soil.

### Materials

Several types of grout have been proposed for this block (Loomis et al. 2002). The properties vary widely depending on the components mixed with the grout and the type of grout. Grout material properties listed in Table C-1 are representative of all grouts and do not represent one particular type.

Table C-1. Grout properties.

Property	Value
Modulus of elasticity <sup>1</sup> ( $E = 57000\sqrt{f'_c}$ )	$4.415 \times 10^6$ psi (635,789 kip/ft <sup>2</sup> )
Density <sup>2</sup>	112 lbf/ft <sup>3</sup> (0.112 kip/ft <sup>3</sup> )
Damping ratio <sup>2</sup>	0.07
Poisson's ratio <sup>2</sup>	0.20

1. ACI 318-02 Sec. 8.5 –  $f'_c$  is estimated to be 6000 psi

2. Estimated

Properties for the soil, listed in Table C-2, are from Idaho Nuclear Technology and Engineering Center (INTEC) soil samples. The soil at RWMC is slightly different in that it has less gravel and will be less stiff. However, for this analysis, the INTEC soil properties were used to approximate these soil conditions.

Table C-2. Soil properties.

Depth	Property	Value
0–10 ft	Weight	0.120 kip/ft <sup>3</sup>
0–10 ft	S-wave velocity	976 ft/sec
0–10 ft	P-wave velocity	1,826 ft/sec
0–10 ft	S-wave damping ratio	0.023
0–10 ft	P-wave damping ratio	0.023
10–20 ft	Weight	0.130 kip/ft <sup>3</sup>
10–20 ft	S-wave velocity	1,481 ft/sec
10–20 ft	P-wave velocity	2,772 ft/sec
10–20 ft	S-wave damping ratio	0.023
10–20 ft	P-wave damping ratio	0.023
Bedrock	Weight	0.150 kip/ft <sup>3</sup>
Bedrock	S-wave velocity	3,640 ft/sec
Bedrock	P-wave velocity	7,393 ft/sec
Bedrock	S-wave damping ratio	0.020
Bedrock	P-wave damping ratio	0.020

## Loads

The block of grout is subjected to a PC-3 history (2,500-year return) scaled for 1,000-, 10,000-, and 100,000-year returns.<sup>a</sup> For this analysis, the vertical time history has been scaled to two thirds of the horizontal. Typically, the vertical and horizontal time histories have different frequency content, but as an approximation for this analysis, they have been scaled. This will give reasonable results for this analysis, but for a more thorough analysis, individual histories would be used.

The PGA for the 2,500-year return period was scaled by the values in Table C-3 for the cases used in this analysis. These values are only for this analysis and should not be construed as valid values for future analyses.

Table C-3. Peak ground acceleration for the 2,500-year return period.

Return Period (years)	Annual Frequency (1/year)	Horizontal PGA (g)	Vertical PGA (g)	Ratio	Scale Factor
1,000	1.0E-03	0.09	0.06	1,000/2,500	0.750
2,500	4.0E-04	0.12	0.08	2,500/2,500	1.0
10,000	1.0E-04	0.19	0.13	10,000/2,500	1.583
100,000	1.0E-05	0.32	0.21	100,000/2,500	2.667

PGA = peak ground acceleration

<sup>a</sup> E-mail from Suzette Payne, August 29, 2002.

## **Assumptions**

The following assumptions were made for this analysis.

1. The history used a PC-3 seismic event at INTEC and a 30-ft soil profile. This is a reasonable approximation for this analysis, but specific time histories should be used for more detailed analysis. There was no soil amplification at any frequency with the block buried below the surface, which gives reasonable results for using this INTEC data.
2. The two-thirds scale factor is adequate for this analysis.
3. The PGAs listed in Table C-3 are for rock. It is assumed reasonable to use it for shallow soil.
4. The PGAs for 10,000- and 100,000-year returns are estimates.

## **Calculations**

A finite element model of this block was created in I-DEAS (SDRC I-DEAS 2002) to generate nodes and elements (see Figure C-1). These nodes and elements were then translated into a SASSI file. The block was modeled half the length in the Y direction to take advantage of symmetry and reduce the solution time. The face in the X-Z plane was fixed from any translations. The block was divided into 600 elements, 300 on each layer, with an edge length approximately 5 ft in each direction. This model has 1,014 nodes in three layers, with 338 nodes per layer.

Transfer functions were generated for six nodes on various parts of the block (see Figure C-2). These transfer functions are shown in Figures C-3 and C-4 for two of the cases analyzed.

The block was evaluated for the following four cases:

1. Block sitting on bedrock with X-direction (horizontal) control motion
2. Block sitting on bedrock with Z-direction (vertical) control motion
3. Block sitting on 5 ft of soil with X-direction control motion
4. Block sitting on 5 ft of soil with Z direction control motion.

The calculated stresses are for the maximum X, Y, or Z direction during the analysis. They are not the principal stresses. The maximum principal stresses will be less than twice the maximum stress. The principal stresses should be compared to the tensile strength of the grout. These stresses are calculated at the center of each element. Results are shown in Table C-4.

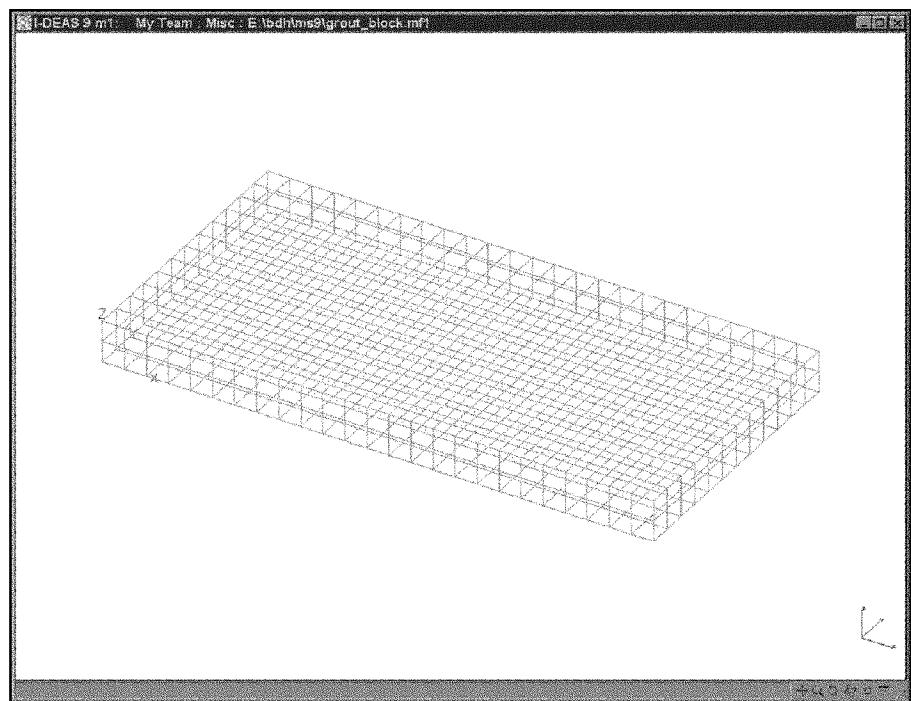


Figure C-1. Finite element model of the grout block. Note that soil elements are not shown.

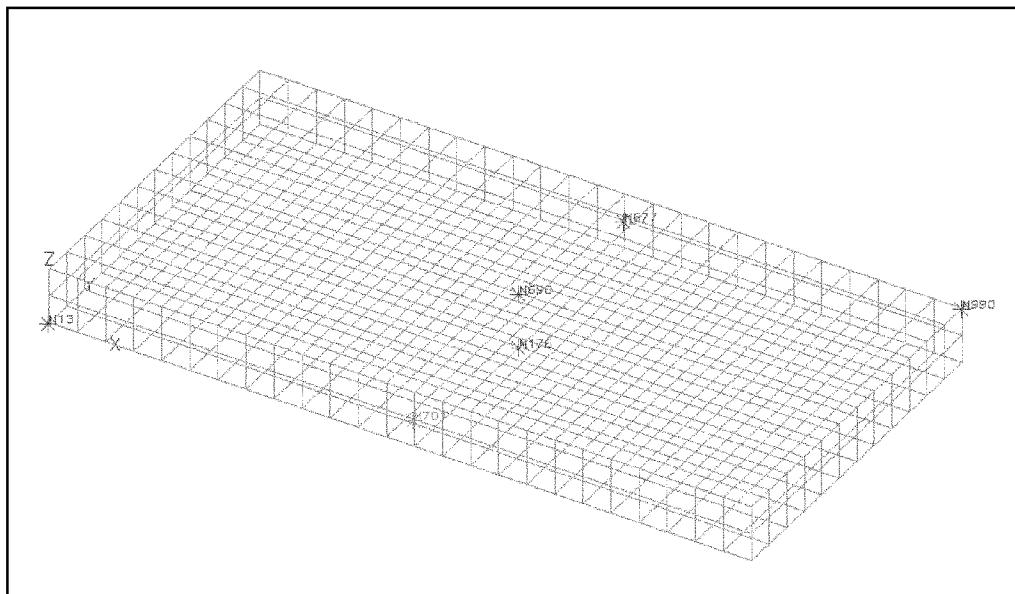


Figure C-2. Node locations selected for transfer functions.

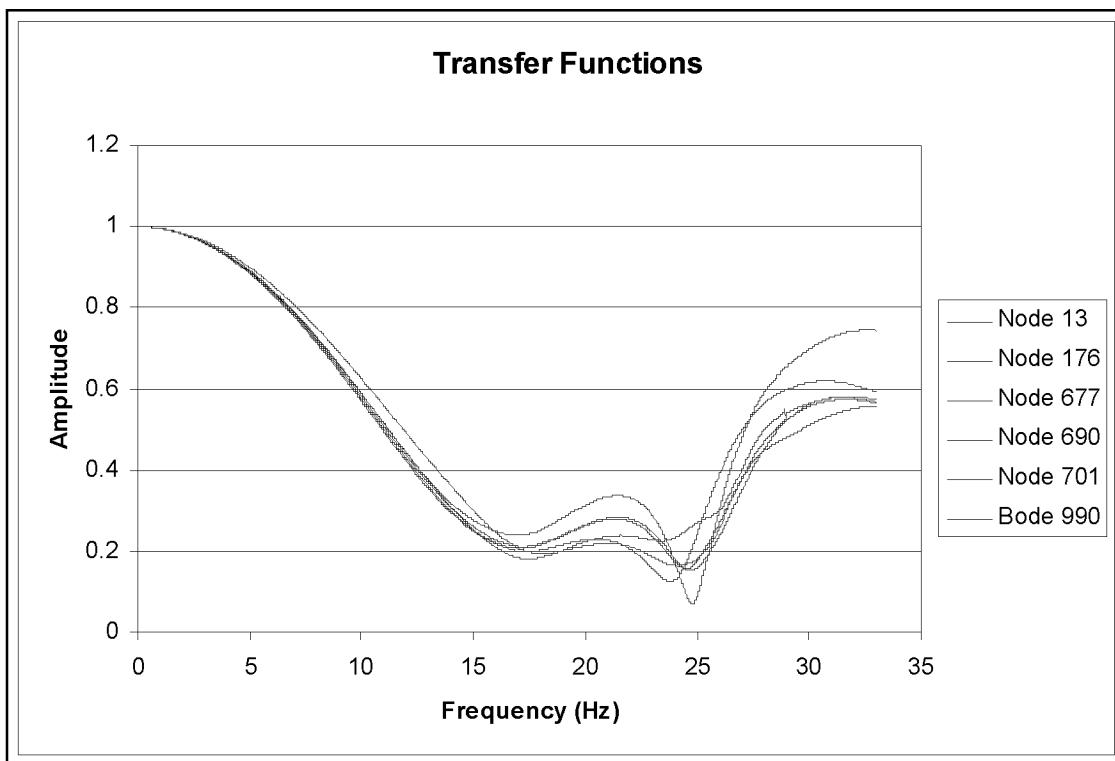


Figure C-3. Transfer functions from block on bedrock with X-direction accelerations.

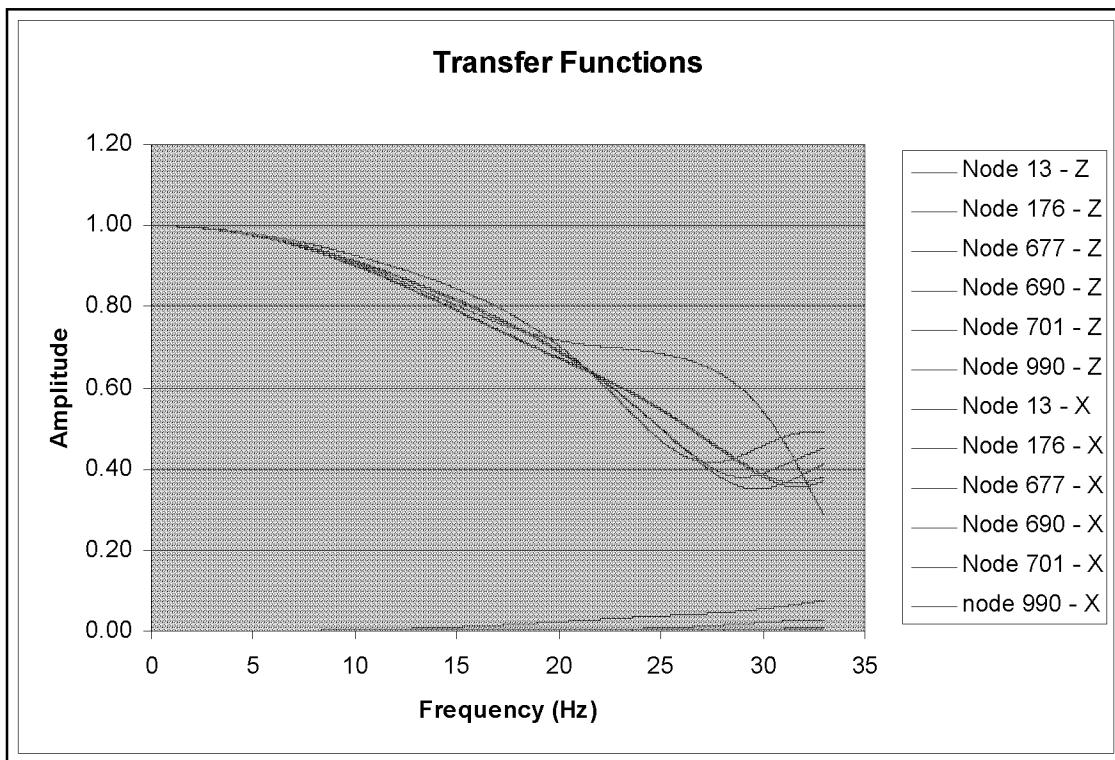


Figure C-4. Transfer functions for block sitting in soil with Z direction accelerations. Results are for the X and Z directions. Note that the X direction responses are very small.

**Table C-4. Principal stresses.**

Block Location – Control motion direction	Time History direction	1,000 Year		10,000 Year		100,000 year	
		Max Stress (psi)	2x Max	Max Stress (psi)	2x Max	Max Stress (psi)	2x Max
Bedrock-X	Horizontal	5.808	11.617	12.257	24.514	20.653	41.306
Bedrock-Z	Vertical	0.355	0.7100	0.749	1.499	1.262	2.524
Soil-X	Horizontal	3.565	7.131	7.528	15.056	12.681	25.361
Soil-Z	Vertical	0.197	0.393	0.415	0.830	0.699	1.397
Soil-Z	Horizontal	0.295	0.590	0.622	1.244	1.048	2.096

## Conclusions

This analysis shows that stresses are quite low compared to the tensile stresses allowed in Table 16 of the *Final Results Report In Situ Grouting Technology for Application in Buried Transuranic Waste Sites, Volume 1, Technology Description and Treatability Study Results for Operable Unit 7-13/14* (Loomis et al. 2002) with the exception of the Enviroblend grout. These results show that the grout block will not crack for the assumptions made.

## Recommendations

It is recommended that a more detailed analysis using SASSI and ABAQUS be performed to verify these answers and determine if cracks will result from seismic events.

## References

- Loomis, G. G., C. M. Miller, A. L. Sehn, J. J. Jessmore, and J. R. Weidner, 2002, *Final Results Report In Situ Grouting Technology for Application in Buried Transuranic Waste Sites, Volume 1, Technology Description and Treatability Study Results for Operable Unit 7-13/14*, INEEL/EXT-02-00233, Rev. 0, Idaho National Engineering and Environmental Laboratory.
- SRDC I-DEAS, 2002, Master Series 9m1, Milford, Ohio.
- SASSI 2000, 1999, *A System for Analysis of Soil-Structure Interaction*, Rev. 1, University of California, Berkeley, California.